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BIOLOGY

NEW SOUTH WALES

STUDENT BOOK

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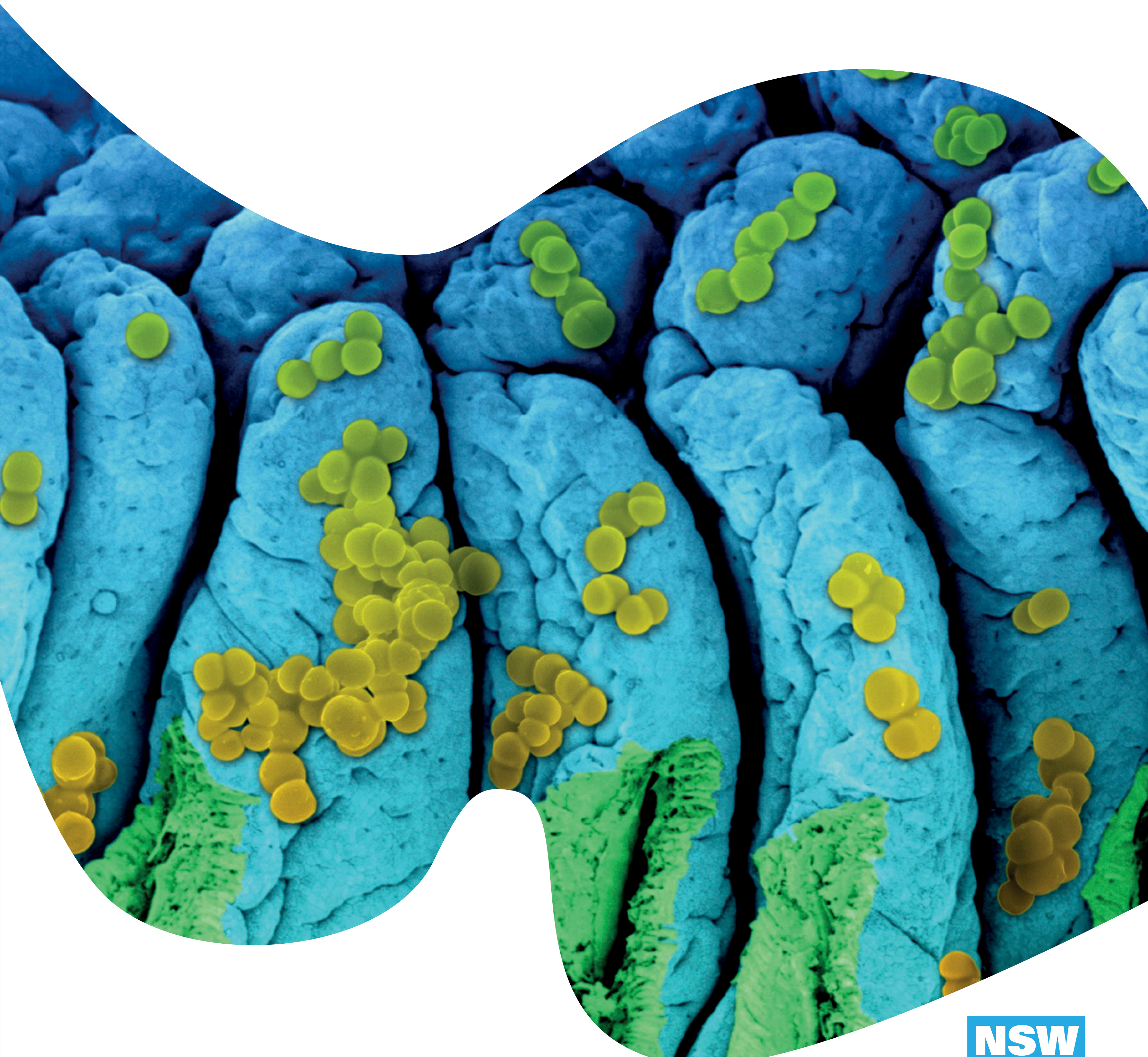

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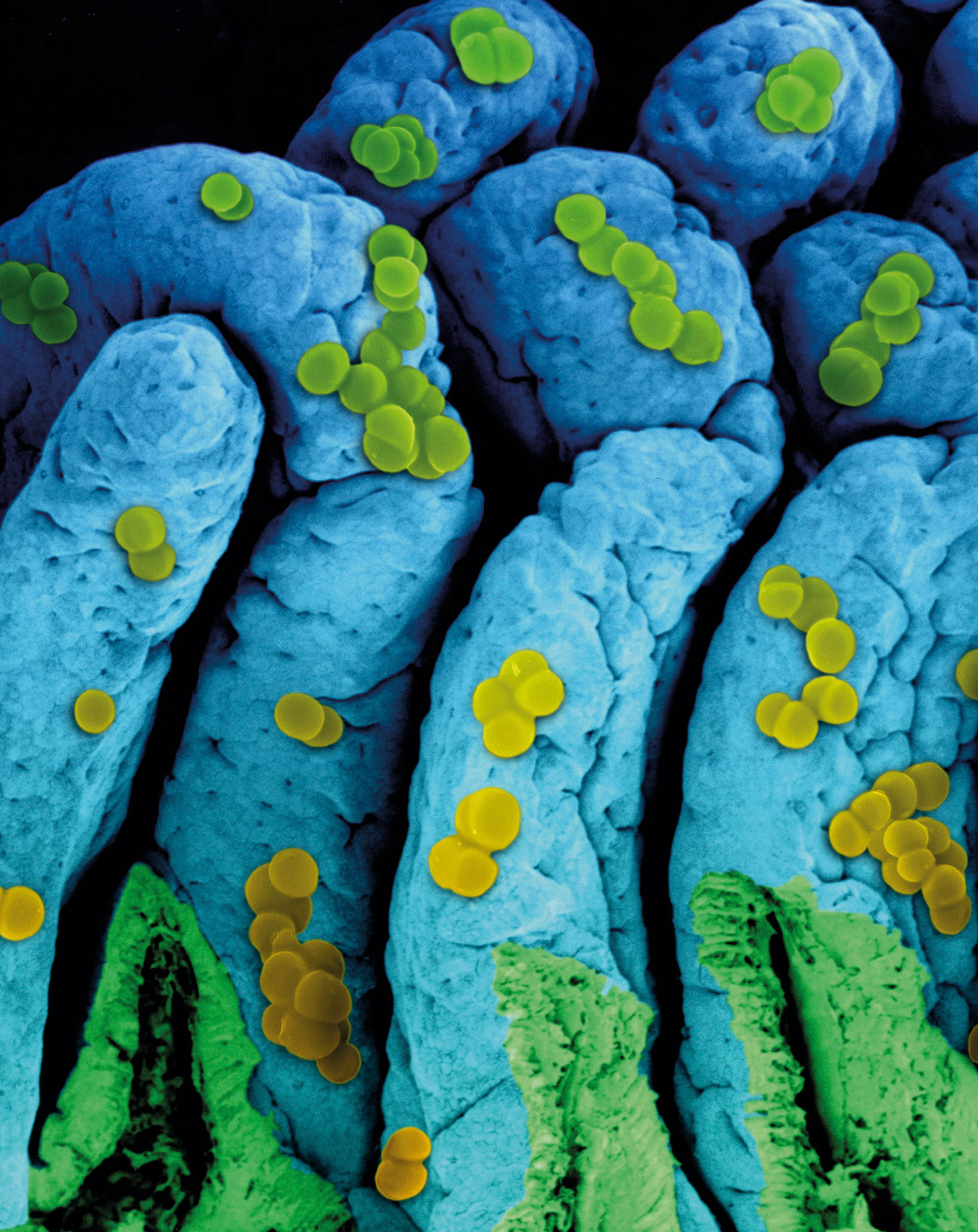

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11

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How to use this book

Pearson Biology 11 New South Wales

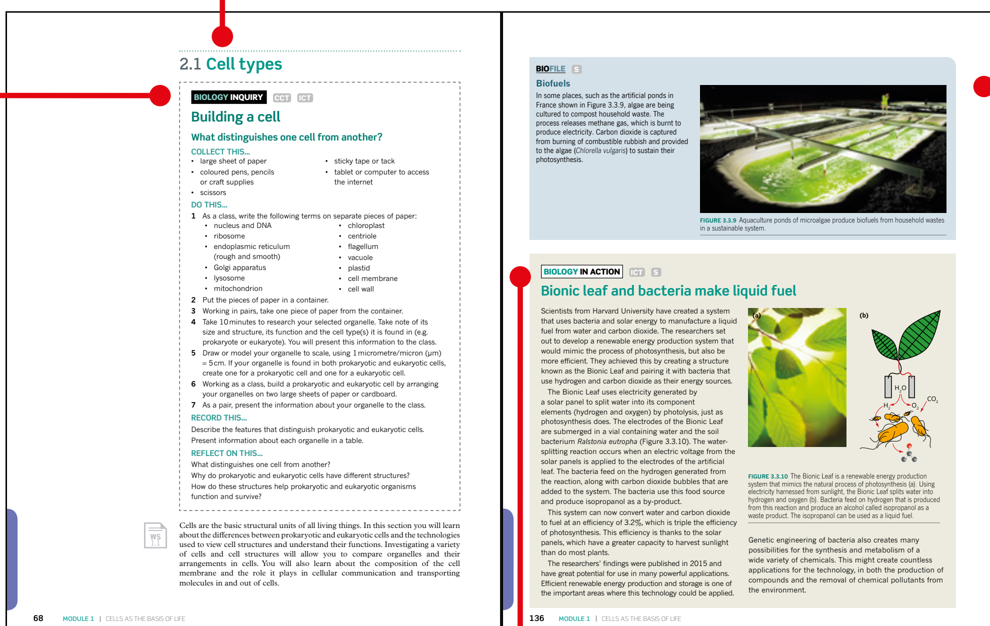
Pearson Biology 11 New South Wales has been written to fully align with the new Stage 6 Syllabus for New South Wales Biology. The book covers Modules 1 to 4 in an easy-to-use resource. Explore how to use this book below.

Chapter opener

The chapter opening page links the Syllabus to the chapter content. Key content addressed in the chapter is clearly listed.

Section

Each chapter is clearly divided into manageable sections of work. Best-practice literacy and instructional design are combined with high-quality, relevant photos and illustrations to help students better understand the idea or concept being developed.



BioFile

BioFiles include a range of interesting and real-world examples to engage students.

Biology Inquiry

Biology Inquiry features are inquiry-based activities that pre-empt the theory and allow students to engage with the concepts through a simple activity that sets students up to 'discover' the science before they learn about it. They encourage students to think about what happens in the world and how science can provide explanations.

Biology in Action

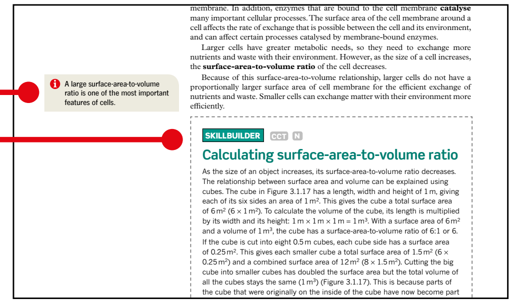
Biology in Action boxes place biology in an applied situation or a relevant context. These refer to the nature and practice of biology, applications of biology and the associated issues, and the historical development of concepts and ideas.

Highlight box

Highlight boxes focus students' attention on important information such as key definitions, formulae and summary points.

SkillBuilder

A SkillBuilder outlines a method or technique. They are instructive and self-contained. They step students through the skill to support science application.

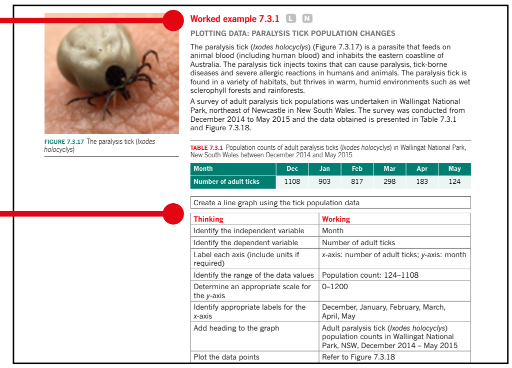


Worked examples

Worked examples are set out in steps that show thinking and working. This format greatly enhances student understanding by clearly linking underlying logic to the relevant calculations.

Each Worked example is followed by a Try yourself activity. This mirror problem allows students to immediately test their understanding.

Fully worked solutions to all Worked example: Try yourself activities are available on *Pearson Biology 11 New South Wales* Reader+.



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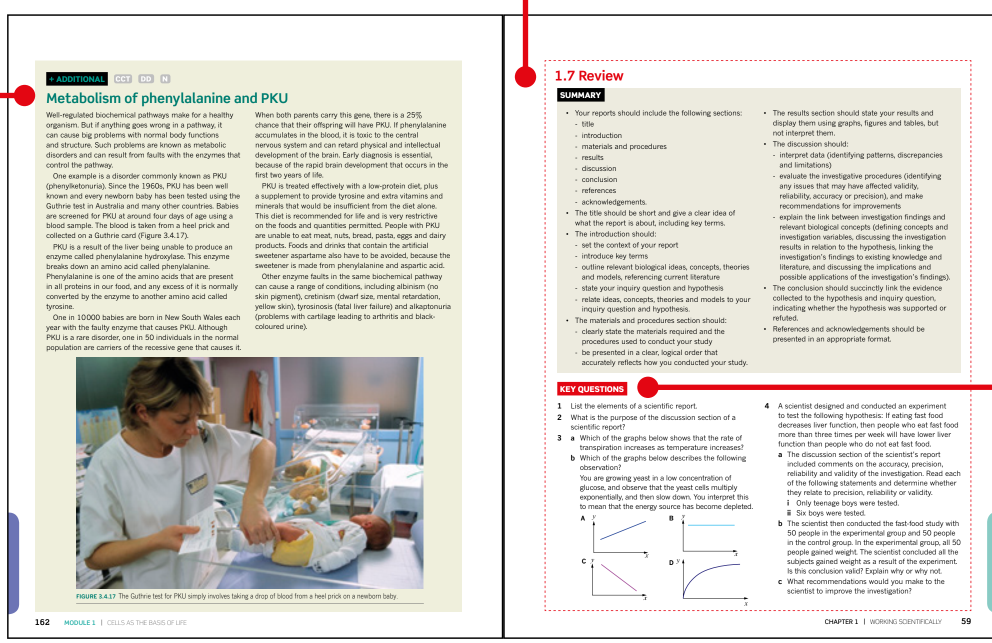
Each section has a summary to help students consolidate the key points and concepts of each section.



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Additional content features include material that goes beyond the core content of the Syllabus. They are intended for students who wish to expand their depth of understanding in a particular area.

Section review questions

Each section finishes with key questions to test students' understanding and ability to recall the key concepts of the section.

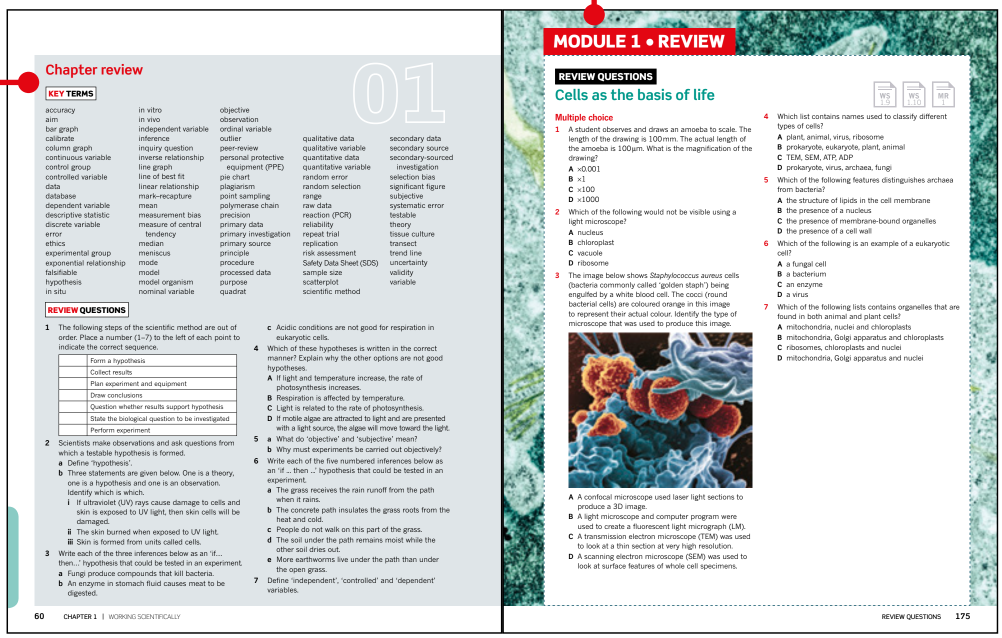
How to use this book

Chapter review

Each chapter finishes with a list of key terms covered in the chapter and a set of questions to test students' ability to apply the knowledge gained from the chapter.

Module review

Each module finishes with a comprehensive set of questions, including multiple choice, short answer and extended response. These assist students in drawing together their knowledge and understanding, and applying it to these types of questions.



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The New South Wales Stage 6 Syllabus 'Learning across the curriculum' and 'General capabilities' content are addressed throughout the series and are identified using the following icons.

AHC A CC CCT DD EU ICT

IU L N PSC S WE

'Go to' icons are used to make important links to relevant content within the same Student Book.

GO TO ➤

This icon indicates the best time to engage with a worksheet (WS), a practical activity (PA), a depth study (DS) or module review (MR) questions in *Pearson Biology 11 New South Wales Skills and Assessment Book*.

WS 3.1

This icon indicates the best time to engage with a practical activity on *Pearson Biology 11 New South Wales* Reader+.

PA 3.2

Glossary

Key terms are shown in **bold** in sections and listed at the end of each chapter. A comprehensive glossary at the end of the book includes and defines all the key terms.

Answers

Comprehensive answers and fully worked solutions for all section review questions, Worked example: Try yourself features, chapter review questions and module review questions are provided via *Pearson Biology 11 New South Wales* Reader+.

Pearson Biology 11
New South Wales

Student Book

Pearson Biology 11 New South Wales has been written to fully align with the new Stage 6 Syllabus for New South Wales Biology. The Student Book includes the very latest developments and applications of biology and incorporates best-practice literacy and instructional design to ensure the content and concepts are fully accessible to all students.

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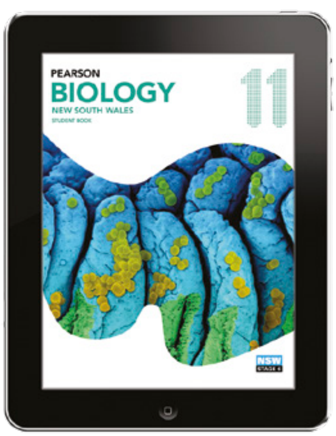

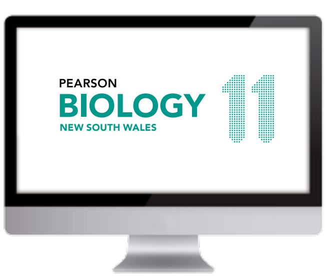

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CHAPTER 01

Working scientifically

This chapter covers the skills needed to plan, conduct and communicate the outcomes of primary and secondary-sourced investigations. Developing, using and demonstrating these skills in a variety of contexts is important when you undertake investigations and evaluate the research of others.

You can use this chapter as a reference as you work through other chapters. It contains useful checklists for when you are drawing scientific diagrams or graphs, or writing a scientific report. Whenever you perform a primary investigation, refer to this chapter to make sure your investigation is valid, reliable and accurate.

1.1 Questioning and predicting covers how to develop, propose and evaluate inquiry questions and hypotheses. When creating a hypothesis, variables must be considered.

1.2 Planning investigations explains how to identify risks and make sure all ethical concerns are considered. It is important to choose appropriate materials and technology to carry out your investigation. You will also need to confirm that your choice of variables allows for reliable data collection.

1.3 Conducting investigations describes procedures for accurately collecting and recording data to reduce errors. It also describes appropriate procedures for disposing of waste.

1.4 Processing data and information describes ways to represent information and explains how to identify trends and patterns in your data.

1.5 Analysing data and information explains error, uncertainty and limitations in scientific data and helps you to assess the accuracy, validity and reliability of your data and the data of others.

1.6 Problem solving is a guide to using modelling and critical thinking to make predictions and demonstrate an understanding of the scientific principles behind your inquiry question.

1.7 Communicating explains how to communicate an investigation clearly and accurately using appropriate scientific language, nomenclature and scientific notation and draw evidence-based conclusions relating to your hypothesis and research question.

Outcomes

By the end of this chapter you will be able to:

- develop and evaluate questions and hypotheses for scientific investigation (BIO11-1)
- design and evaluate investigations in order to obtain primary and secondary data and information (BIO11-2)
- conduct investigations to collect valid and reliable primary and secondary data and information (BIO11-3)
- select and process appropriate qualitative and quantitative data and information using a range of appropriate media (BIO11-4)
- analyse and evaluate primary and secondary data and information (BIO11-5)

- solve scientific problems using primary and secondary data, critical thinking skills and scientific processes (BIO11-6)
- communicate scientific understanding using suitable language and terminology for a specific audience or purpose (BIO11-7)

Content

By the end of this chapter you will be able to:

- develop and evaluate inquiry questions and hypotheses to identify a concept that can be investigated scientifically, involving primary and secondary data (ACSBL001, ACSBL061, ACSBL096) L
- modify questions and hypotheses to reflect new evidence CCT
- assess risks, consider ethical issues and select appropriate materials and technologies when designing and planning an investigation (ACSBL031, ACSBL097) EU PSC
- justify and evaluate the use of variables and experimental controls to ensure that a valid procedure is developed that allows for the reliable collection of data (ACSBL002)
- evaluate and modify an investigation in response to new evidence CCT
- employ and evaluate safe work practices and manage risks (ACSBL031) PSC WE
- use appropriate technologies to ensure and evaluate accuracy ICT N
- select and extract information from a wide range of reliable secondary sources and acknowledge them using an accepted referencing style L
- select qualitative and quantitative data and information and represent them using a range of formats, digital technologies and appropriate media (ACSBL004, ACSBL007, ACSBL064, ACSBL101) L N
- apply quantitative processes where appropriate N
- evaluate and improve the quality of data CCT N
- derive trends, patterns and relationships in data and information
- assess error, uncertainty and limitations in data (ACSBL004, ACSBL005, ACSBL033, ACSBL099) CCT
- assess the relevance, accuracy, validity and reliability of primary and secondary data and suggest improvements to investigations (ACSBL005) CCT N
- use modelling (including mathematical examples) to explain phenomena, make predictions and solve problems using evidence from primary and secondary sources (ACSBL006, ACSBL010) CCT
- use scientific evidence and critical thinking skills to solve problems CCT
- select and use suitable forms of digital, visual, written and/or oral forms of communication L N
- select and apply appropriate scientific notations, nomenclature and scientific language to communicate in a variety of contexts (ACSBL008, ACSBL036, ACSBL067, ACSBL102) L N
- construct evidence-based arguments and engage in peer feedback to evaluate an argument or conclusion (ACSBL034, ACSBL036) CC DD

1.1 Questioning and predicting

FIGURE 1.1.1 An entomologist (a scientist who studies insects) collects insects from the top of a tropical rainforest tree.

Biology is the study of living organisms. As scientists, biologists extend their understanding using the scientific method, which involves investigations that are carefully designed, carried out and reported. Well-designed research is based on a sound knowledge of what is already understood about a subject, as well as careful preparation and observation (Figure 1.1.1).

When beginning an investigation, you must first develop and evaluate an **inquiry question** and **hypothesis**, and determine the **purpose** of the investigation. It is important to understand that each of these can be refined as the planning of your investigation continues.

- The inquiry question defines what is being investigated. For example: Is the rate of transpiration in plants dependent on temperature?
- The hypothesis is a tentative explanation for an observation that is based on prior knowledge or evidence. For example: If transpiration rates in plants increase with increasing temperature and the air temperature is raised from 20°C to 40°C, then transpiration and water loss from a plant will increase. A hypothesis must be **testable** and **falsifiable** (can be proven false). You'll learn more about hypotheses on page 9.
- The purpose (also known as the **aim**) is a statement describing in detail what will be investigated. For example: To investigate the effect of temperature on the rate of transpiration in plants at 20°C, 30°C and 40°C.

This section will introduce you to developing and evaluating inquiry questions and hypotheses to investigate scientifically.

TYPES OF INVESTIGATIONS

Many different types of investigations can be conducted in biology. You are probably most familiar with practical investigations or experiments. An investigation that you conduct yourself is known as a **primary investigation**, and the **data** and information you collect is called **primary data** or a **primary source**.

Inquiry questions can also be answered by researching and evaluating data that others have collected. Data or information that was collected by someone else is known as **secondary data** or a **secondary source**. An investigation that uses secondary data is known as a **secondary-sourced investigation**.

Examples of different types of investigations are listed in Table 1.1.1 and Table 1.1.2.

TABLE 1.1.1 Examples of primary investigations

	Example tasks
conducting experiments in a laboratory	planning a valid experiment, conducting a risk assessment, working safely, recording observations and results, analysing and evaluating data and information
conducting fieldwork	conducting a risk assessment, working safely, recording observations and results, analysing and evaluating data and information
conducting surveys	writing questions, collecting data, analysing data and information
designing a model	identifying a problem to be modelled, summarising key findings, identifying advantages and limitations of the model

TABLE 1.1.2 Examples of secondary-sourced investigations

	Example tasks
researching published data from primary and secondary sources	finding published information in scientific magazines and journals, books, databases, media texts and labels of commercially available products; analysing and evaluating data and information

Before you start the practical side of your investigation, you must first understand the biological concepts that underlie it.

LEARNING THROUGH INVESTIGATION

Scientists make observations and then ask questions that can be investigated. Using their knowledge and experience, scientists suggest possible explanations for the things they observe. A possible explanation is called a hypothesis. A hypothesis can be used to make certain predictions. Often these predictions can be tested experimentally. This experimental approach to the study of science is called the **scientific method** (Figure 1.1.2).

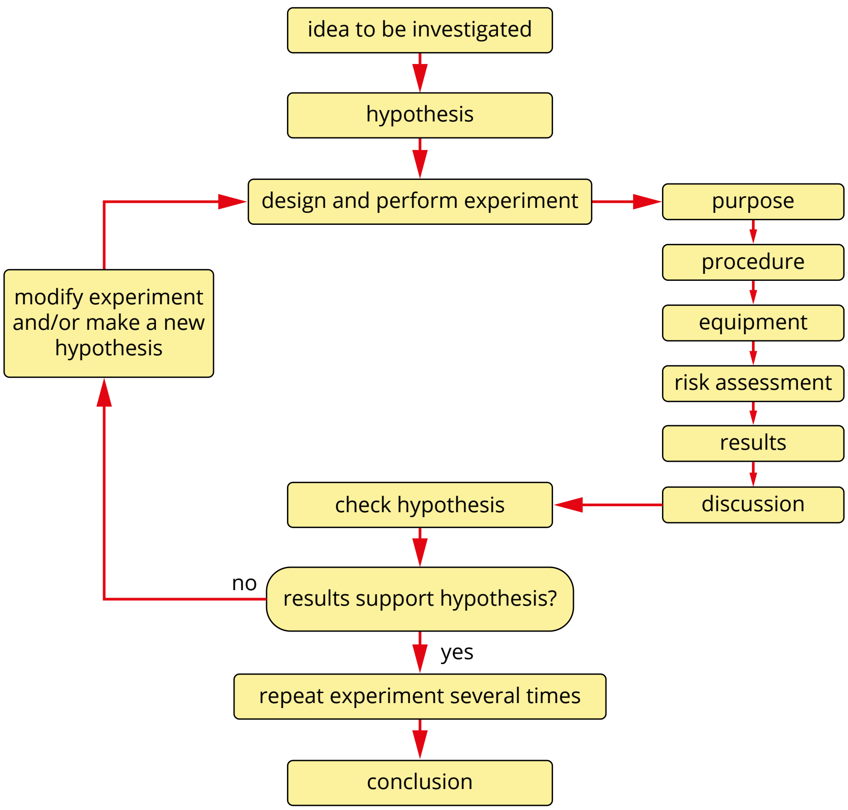

FIGURE 1.1.2 The scientific method is based on asking questions that can be answered experimentally.

To determine whether their predictions are accurate or not, a scientist carries out carefully designed experiments. If the results of an experiment do not fall within an acceptable range, the hypothesis is rejected. If the predictions are found to be accurate, the hypothesis is supported. If, after many different experiments, one hypothesis is supported by all the results obtained so far, then this explanation can be given the status of a **theory** or **principle**.

There is nothing mysterious about the scientific method. You might use the same process to find out how unfamiliar technology works if you had no instructions. Careful observation is usually the first step.

OBSERVATION

Observation includes using all your senses and the instruments available to allow closer inspection of things that the human eye cannot see. Through careful inquiry and observation, you can learn a lot about organisms, the ways they function, and their interactions with each other and their environment. For example, animals function very differently from plants. Animals usually move around, take in nutrients and water, and often interact with each other in groups. We find them in water, on land and flying in the air. Some are fast, efficient predators (Figure 1.1.3).

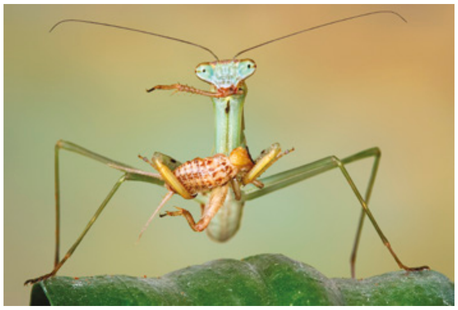

FIGURE 1.1.3 The praying mantis is a fast, efficient predator. Its green colouration and leaf-like shape give it the deadly advantage of camouflage. These features of the praying mantis can be observed and investigated.

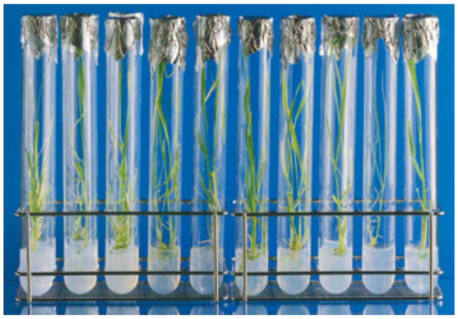

FIGURE 1.1.4 Laboratory procedures, such as plant tissue culture, rely on careful observations and data collection to understand the requirements for plant growth. Laboratory investigations then provide new information that can be applied to plants growing in the field.

Plants, meanwhile, are usually green, stationary and turn their leaves towards the light as they grow. Sometimes they lose all their leaves, and then grow new ones. Many develop flowers and fruit for reproduction. All of these things can be learnt from simple observation.

The idea for a primary investigation of a complex problem arises from prior learning and observations that raise further questions. For example, indoor plants do not grow well without artificial lighting. This suggests that plants need light to photosynthesise. By researching this aspect of photosynthesis, new knowledge can be used in other applications, such as **procedures** for growing plants in the laboratory for genetic selection and modification for crop improvement (Figure 1.1.4).

INQUIRY QUESTIONS

How observations are interpreted depends on past experiences and knowledge. But to enquiring minds, observations will usually provoke further questions, such as those given below.

- How do organisms gain and expend energy?
- Are there differences between cellular processes in plants, animals, bacteria, fungi and protists?
- How do multicellular organisms develop specialised tissues?
- What are the molecular building blocks of cells?
- How do species change and evolve over time?
- How do cells communicate with each other?
- What is the molecular basis of heredity, and how is this genetic information decoded?

Many of these questions cannot be answered by observation alone, but they can be answered through scientific investigations. Lots of great discoveries have been made when a scientist has been busy investigating another problem. Good scientists have acute powers of observation and enquiring minds, and they make the most of these chance opportunities.

Before conducting an investigation, you need an inquiry question to address. An inquiry question defines what is being investigated. For example, what is the relationship between a plant's exposure to sunlight and the rate of the plant's growth?

Choosing a topic

When you choose a topic, consider the following suggestions.

- Choose an inquiry question you find interesting.
- Start with a topic for which you already have some background information, or some clues about how to perform the experiments.
- Check that your school laboratory has the resources for you to perform the experiments or investigate the topic.
- Choose a topic that can provide clear, measurable data.

You will learn more about useful research techniques in Section 1.3.

GO TO ➤ Section 1.3 page 20

Asking the right questions

In science, there is little value in asking questions that cannot be answered. An experimental hypothesis must be testable. If you consider a question such as 'How do bats navigate at night?', then the statement 'Bats use thought waves to navigate' is not possible to test. Instead, a testable hypothesis might be 'If bats use hearing to navigate, then they will not be able to navigate if they cannot hear'.

In 1793, Italian scientist Lazzaro Spallanzani wondered about this question, and set about testing the hypothesis. He found that if he plugged their ears, the bats collided into obstacles, but if the plugs had a hole that allowed the bats to hear, then they flew normally. He concluded that bats used their ears to detect obstacles and prey at night. It wasn't until 1938 that English physiologist Hamilton Hartridge detected the ultrasonic signals made by bats, thereby allowing us to understand how bats use their hearing to navigate.

You must also ask the right questions to get answers that are relevant to the problem you are examining. For example, there is no point in asking how long bats live when you are studying how they navigate, as the information you obtain will not be useful for testing your hypothesis.

Developing your inquiry question

It is important to work out exactly what an inquiry question is asking you to do. You need to:

- identify a 'guiding' word, such as *who*, *what*, *where*, *why*
- link the guiding word to command verbs, such as *identify*, *describe*, *compare*, *contrast*, *distinguish*, *analyse*, *evaluate*, *predict*, *develop* and *create*.

Some examples of inquiry questions are provided in Table 1.1.3.

TABLE 1.1.3 Examples of inquiry questions for primary or secondary investigations

Guiding word	Example inquiry questions	What are you being asked to do? What are the command verbs?
what	**What** distinguishes one cell from another?	Identify and describe specific examples, evidence, reasons and analogies from a variety of possibilities. *Identify* and *describe*.
where	**Where** are blue triangle butterflies distributed?	Identify and describe, giving reasons for a place or location. *Identify* and *describe*.
how	**How** do selection pressures within an ecosystem influence evolutionary change?	Identify and describe in detail a process or mechanism. Give examples using evidence and reasons. *Identify* and *describe*.
why	**Why** is polypeptide synthesis important?	Identify and describe in detail the causes, reasons, mechanisms and evidence. *Identify* and *describe*.
would	**Would** there be life if elements did not form compounds?	Evaluate evidence. Justify your answer by giving reasons for and against (using evidence, analogies, comparisons). *Evaluate* and *justify*.
is/are	**Is** there a relationship between evolution and biodiversity? **Are** there more species to be discovered?	Evaluate evidence. Justify your answer by giving reasons. *Evaluate* and *justify*.
on what basis	**On what basis** are new species named?	Identify and describe examples. Distinguish between reliable and unreliable evidence. *Identify, describe* and *distinguish*.
can	**Can** population genetic patterns be predicted with any accuracy?	Analyse and evaluate evidence. Justify your answer by giving reasons. Create a diagram to support your answer. Suggest possible alternatives. *Analyse, evaluate, justify* and *create*.
do/does	**Do** non-infectious diseases cause more deaths than infectious diseases? **Does** artificial manipulation of DNA have the potential to change populations forever?	Evaluate evidence. Justify using reasons and evidence for and against. Compare and contrast. *Evaluate, justify, compare* and *contrast.*
should	**Should** we manage and conserve biodiversity?	Identify and evaluate pros and cons, implications and limitations. Make a judgement. Critically assess evidence and develop an argument to support your position. Use reliable evidence to justify your conclusion. *Identify, evaluate, assess, develop* and *justify*.
might	What **might** we do if fishery stocks run out?	Evaluate evidence. Justify your answer by giving reasons for and against (using evidence, analogies, comparisons). Create a graph and predict the outcomes of different scenarios. *Evaluate, justify, compare, create* and *predict.*

Once you come up with a topic or idea of interest, the first thing you need to do is conduct a literature review. This means reading scientific reports and other articles on the topic to find out what is already known, and what is not known or not yet agreed upon. The literature also gives you important information you can use for the introduction to your report and ideas for experimental procedures.

A literature review is an analysis of secondary data or information. While you are reviewing the literature, write down any questions or correlations you find. Compile a list of possible ideas. Do not reject ideas that initially may seem impossible, but use these ideas to generate questions.

When you have defined an inquiry question, you first need to evaluate it. Then, you will be able to come up with a hypothesis, identify the measurable variables, design your investigation and experiments, and suggest a possible outcome.

Evaluating your inquiry question

Stop to evaluate your inquiry question before you start planning the rest of your study. You might need to refine your question further or conduct some more investigations before deciding whether the question is suitable as a basis for an achievable, worthwhile investigation. Use the following list when evaluating your inquiry question:

- Relevance—your question must be related to your chosen topic. For your practical investigation, decide whether your question will relate to cellular structure or organisation, or to structural, physiological or behavioural adaptations of an organism to an environment.
- Clarity and measurability—your question must be able to be framed as a clear hypothesis. If the question cannot be stated as a specific hypothesis, then it is going to be very difficult to complete your research.
- Time frame—make sure your question can be answered within a reasonable period of time. Ensure your question isn't too broad.
- Knowledge and skills—make sure you have a level of knowledge and a level of laboratory skills that will allow you to explore the question. Keep the question simple and achievable.
- Practicality—check the resources you require, such as reagents and laboratory equipment, are going to be available. You may need to consult your teacher. Keep things simple. Avoid investigations that require sophisticated or rare equipment. Common laboratory equipment may include thermometers, photometers and light microscopes.
- Safety and ethics—consider the safety and ethical issues associated with your question. If there are any issues, determine if these need to be addressed.
- Advice—seek advice from your teacher on your question. Their input may prove very useful. Your teacher's experience may lead them to consider aspects of the question that you have not thought about.

DEFINING YOUR VARIABLES

The factors that can change during your experiment or investigation are called the **variables**. An experiment or investigation determines the relationship between variables, measuring the effects of one variable on another. There are three categories of variables:

- **independent variable**—a variable that is controlled by the researcher (the variable that is selected and changed)
- **dependent variable**—a variable that may change in response to a change in the independent variable, and is measured or observed
- **controlled variables**—the variables that are kept constant during the investigation.

You should have only one independent variable. Otherwise, you could not be sure which independent variable was responsible for changes in the dependent variable. Variables and controlled experiments are discussed further in Section 1.2.

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Qualitative and quantitative variables

Variables are described as either qualitative or quantitative. There are also further subsets in each category of variables.

- **Qualitative variables** (or categorical variables) can be observed but not measured. They can only be sorted into groups or categories such as flower colour or leaf shape. Qualitative variables can be nominal or ordinal.
  - **Nominal variables** are variables in which the order is not important; for example, eye colour.
  - **Ordinal variables** are variables in which order is important and groups have an obvious ranking or level; for example, a person's body mass index.
- **Quantitative variables** can be measured. Height, mass, volume, temperature, pH and time are all examples of quantitative data. Discrete and continuous variables are types of quantitative variables.
  - **Discrete variables** consist of only integer numerical values, not fractions; for example, the number of nucleotides in a sequence of DNA.
  - **Continuous variables** allow for any numerical value within a given range; for example, the measurement of height, temperature, volume, mass and pH.

  You will learn more about data and variable types in Section 1.4.

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HYPOTHESES

A hypothesis is a tentative explanation for an observation that is based on evidence and prior knowledge. A hypothesis must be testable and falsifiable. It defines a proposed relationship between two variables.

Developing your hypothesis

To develop a hypothesis, you need to identify the dependent and independent variables. A good hypothesis is written in terms of the dependent and independent variables: e.g. If x is true and I test this, then y will happen.

For example:

IF there is a positive relationship between light and the rate of photosynthesis, and the rate of photosynthesis is estimated by measuring the oxygen output of a plant, THEN the oxygen output of a plant will be higher when it is in the light than when it is in the dark.

- The 'if' at the beginning of the hypothesis indicates that the statement is tentative. This means that it is uncertain and requires testing to confirm. This first part of the hypothesis is based on an educated guess and refers to the relationship between the independent and dependent variable (e.g. IF there is a positive relationship between light and the rate of photosynthesis). In this example, light is the independent variable and the rate of photosynthesis is the dependent variable.
- When writing a hypothesis, consider how it will be tested. The outcome of the test needs to measurable (e.g. by measuring a plant's oxygen output when it is in the dark and when it is exposed to light).
- A hypothesis should end with a statement of the measurable, predicted outcome (e.g. the oxygen output of a plant will be lower when it is in the dark than when it is exposed to light).

A good hypothesis can be tested to determine whether it is true (verified or supported), or false (falsified or rejected) by investigation. To be testable, your hypothesis needs to include variables that are measurable.

> Hypotheses can be written in a variety of ways, such as 'x happens because of y' or 'when x happens, y will happen'. However they are written, hypotheses must always be testable and clearly state the independent and dependent variables.

Writing a hypothesis from an inference

Scientists often develop a hypothesis by **inference** (reasoning) based on preliminary observations. For example, in summer, the colour of grasses usually changes from green to brown or yellow. One observation is that grass growing near the edges of a concrete path stays green for longer than grass further from the edges (Figure 1.1.5).

FIGURE 1.1.5 The grass closer to the concrete and in between the cracks of the concrete is green. This is an observation from which a hypothesis can be developed.

A valid inference is one that explains all the observations. The following inferences may explain why grass growing near the edge of the concrete path remains green in summer.

- Inference 1: The grass receives the runoff water from the path when it rains.
- Inference 2: The concrete path insulates the grass roots from the heat and cold.
- Inference 3: People do not walk on the grass growing near the edge of the path.

For Inference 1, the hypothesis might be: 'If grass needs water to remain green, then grass that doesn't receive rainwater runoff will turn brown while grass that receives rainwater runoff will remain green.'

Creating a table like Table 1.1.4 will help you evaluate your inquiry question, the variables you might consider, and the potential hypothesis you could use to guide your investigation.

TABLE 1.1.4 Summary table of inquiry question, variables and potential hypothesis

Inference	Research question	Independent variable	Dependent variable	Controlled variables	Potential hypothesis
Plants growing in soil with fertiliser added are taller than plants growing in soil without fertiliser added.	Does fertiliser make plants grow taller?	fertiliser	plant height	type of plant, soil, temperature, water and sunlight	If fertiliser makes plants grow taller and fertiliser is added to the soil, then plant X will grow taller.

PURPOSE

The purpose (also known as the aim) is a statement describing what will be investigated. The purpose should directly relate to the variables in the hypothesis, and describe how each variable will be studied or measured. The purpose does not need to include the details of the procedure.

Determining your purpose

To determine the purpose of your investigation, first identify the variables in your hypothesis.

Example 1:

- Hypothesis: If transpiration rates in plants increase with increasing air temperature and the air temperature is increased, then the rate of transpiration in plants will also increase.
- Variables: temperature (independent) and transpiration rate (dependent).
- Purpose: To compare the rate of transpiration of corn seedlings in air temperatures of 15°C, 25°C, 35°C and 45°C over 24 hours.

Example 2:

- Hypothesis: If bees are more attracted to the colour red than to the colour blue, then red flowers will attract more bees than blue flowers.
- Variables: colour of flowers (independent) and number of bees attracted to a flower (dependent).
- Purpose: To compare the number of bees visiting red flowers to the number of bees visiting blue flowers over a period of time.

1.1 Review

SUMMARY

- Well-designed experiments are based on a sound knowledge of what is already understood or known and careful observation.
- An investigation that you conduct yourself is known as a primary investigation, and the data you collect is called primary data.
- An investigation that uses data collected by someone else is known as a secondary-sourced investigation.
- Scientific investigations are undertaken to answer inquiry questions.
- Inquiry questions define what is being investigated.
- A primary investigation determines the relationship between variables by measuring the results.
- The scientific method is an accepted procedure for conducting experiments.
- The three types of variables are:
  - independent—a variable that is controlled by the researcher (the one that is selected and changed)
  - dependent—a variable that may change in response to a change in the independent variable, and is measured or observed
  - controlled—the variables that are kept constant during the investigation.
- The hypothesis is a tentative explanation for an observation based on previous knowledge and evidence. A hypothesis must be testable and falsifiable.
- Scientific investigations are undertaken to test hypotheses. The results of an investigation may support or reject a hypothesis, but cannot prove it to be true in all circumstances.
- The purpose is a statement that describes in detail what will be investigated.

KEY QUESTIONS

1 What is the scientific method based on?
   A observation
   B subjective decisions
   C manipulation of results
   D generalisations

2 It is important to evaluate and revise your inquiry question and hypothesis when conducting an investigation. What are three things to consider when evaluating your inquiry question?

3 Which of the following is an important part of conducting an experiment?
   A disregarding results that do not fit the hypothesis
   B making sure the experiment can be repeated by others
   C producing results that are identical to each other
   D changing the results to match the hypothesis

4 Write a hypothesis for each of the following purposes:
   a to test whether carrot seeds or tomato seeds germinate quicker
   b to test whether sourdough, multigrain or white bread goes mouldy the fastest
   c to test whether Trigg the dog likes dry food or fresh food better

5 Select the best hypothesis, and explain why the other options are not good hypotheses.
   A If light and temperature increase, then the rate of photosynthesis increases.
   B Transpiration is affected by temperature.
   C Light is related to the rate of photosynthesis.
   D If temperature positively affects the rate of photosynthesis, then a plant's output of oxygen will increase as temperature increases.

6 **a** State the meaning of the term 'variable'.
   b Copy and complete the table below with definitions of the types of variables.

Independent variable	Controlled variable	Dependent variable

7 Identify the independent, dependent and controlled variables that would be needed to investigate each of the following hypotheses:
   a If the rate of transpiration is positively affected by temperature, then an increase in temperature will lead to an increase in the rate of transpiration in plants.
   b If photosynthesis is dependent on light and there is no light, then there will be no photosynthesis in the leaves of a plant.
   c If a lid on a cup prevents heat loss from the cup and a cup of hot chocolate has a lid on it, then it will stay hot for a longer period of time.
   d If the amount of wax in a candle increases burn time and a thin candle and a thick candle are lit at the same time, then the thin candle will melt faster.

1.2 Planning investigations

FIGURE 1.2.1 A microbiologist in the field collecting soil samples to test for bacteria in the East Kimberley, Western Australia

Once you have formulated your hypothesis, you will need to plan and design your investigation. Taking the time to carefully plan and design a practical investigation before beginning will help you to maintain a clear and concise focus throughout (Figure 1.2.1). Preparation is essential. This section is a guide to some of the key steps that should be taken when planning and designing a practical investigation.

WRITING A PROTOCOL AND SCHEDULE

Once you have determined your inquiry question, variables, hypothesis and purpose, you should write a detailed description of how you will conduct your experiment. This description is also known as a **protocol**. You should also create a work schedule that outlines the time frame of your experiments, being sure to include sufficient time to repeat experiments if necessary. Check with your teacher that your protocol and schedule are appropriate, and that others will be able to repeat your experiment exactly by following the protocol you have written.

Test your protocol, and evaluate and modify it if necessary. When writing your protocol, consider the time, space, equipment, resources and teacher or peer support you will need to conduct your investigation. Quantitative results are preferable for high-quality, reproducible science. Therefore, if possible, you should use procedures that enable you to count, measure or grade what you observe.

EVALUATING THE PROCEDURE

The procedure (also known as the method) is the step-by-step procedure followed to carry out the investigation. When detailing the procedure, make sure it will allow for a valid, reliable and accurate investigation.

Procedures must be described clearly and in sufficient detail to allow other scientists to repeat the experiment. If other scientists cannot obtain similar results when an experiment is repeated and the results averaged, then the experiment is considered unreliable. It is also important to avoid personal bias that might affect the collection of data or the analysis of results. A good scientist works hard to be **objective** (free of personal bias) rather than **subjective** (influenced by personal views). The results of an experiment must be clearly stated and must be separate from any discussion of the conclusions that are drawn from the results.

In science, doing an experiment once is not usually sufficient. You can have little confidence in a single result, because the result might have been due to some unusual circumstance that occurred at the time. The same experiment is usually repeated several times and the combined results are then analysed using statistics. If the statistics show that there is a low probability (less than 5%, referred to as $P < 0.05$) that the results occurred by chance, then the result is accepted as being significant.

> Experiments and their results must be validated. This means they must be able to be repeated by other scientists.

Validity

Validity refers to whether an experiment or investigation is actually testing the set hypothesis and purpose. Is the investigation obtaining data that is relevant to the question? For example, if you think you have measured a variable but have actually measured something else, then the results are invalid. Factors influencing validity include:

- whether your experiment measures what it claims to measure (i.e. your experiment should test your hypothesis)
- whether the independent variable influenced the dependent variable in the way you thought it would (i.e. the certainty that something observed in your experiment was the result of your experimental conditions, and not some other cause that you did not consider)
- the degree to which your findings can be generalised to the wider population from which your sample is taken, or to a different population, place or time.

Controls

It is difficult—sometimes impossible—to eliminate all variables that might affect the outcome of an experiment. In biology, such variables might include time of day, temperature, amount of light, season and level of noise. A way to eliminate the possibility that random factors affect the results is to set up a second group within the experiment, called a **control group**. The control group is identical to the first group (the **experimental group**) in every way, except that the single experimental (independent) variable that is being tested is not changed. This is called a controlled experiment. Because it allows us to examine one variable at a time, a controlled experiment is an important way of testing a hypothesis.

To ensure an investigation is valid, it should be designed so that only one variable is changed at a time. The remaining variables must remain constant, so that meaningful conclusions can be drawn about the effect of each variable.

To ensure validity, carefully evaluate the:

- independent variable (the variable that will be changed), and how it will change
- dependent variable (the variable that will be measured)
- controlled variables (the variables that must remain constant), and how they will be maintained.

> The experimental conditions of the control group are identical to the experimental group, except that the variable of interest (the independent variable) is also kept constant in the control group.

> In an experiment, controlled (fixed) variables are kept constant. Only one variable (the independent variable) is changed. The dependent variable is then measured to determine the effect of that change.

Randomisation

Random selection of your sample improves the validity of your investigation by reducing **selection bias**. Selection bias occurs when your sample doesn't reflect the wider population that you wish to generalise your results to. For example, if you were scoring phenotypes in large trials of genetically selected or genetically modified crop plants, choosing plants at random locations throughout the field would be more valid than choosing plants only at the edges of the field.

Reliability

Reliability (sometimes called repeatability) is the ability to obtain the same averaged results if an experiment is repeated (Figure 1.2.2). Because a single measurement or experimental result could be affected by errors, **replicating** samples within an experiment and running **repeat trials** makes an investigation more reliable. To improve reliability, you should:

- specify the materials and procedures in detail
- include replicate (several) samples within each experiment
- take repeat readings of each sample
- run the experiment or trial more than once.

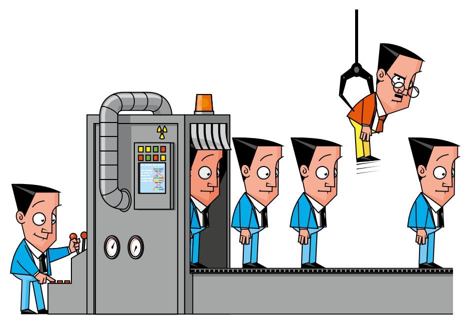

FIGURE 1.2.2 If you can reproduce your results using the same experimental procedures, then they are reliable.

MODIFYING THE PROCEDURE

Your procedure may need to be modified during the investigation. The following actions will help to determine any problems with your procedure and how to modify them.

- Record everything.
- Be prepared to make changes to the approach.
- Note any difficulties encountered and the ways they were overcome. What were the failures and successes? Every test can help you understand more about the investigation, no matter how much of a disaster it may first appear.
- Do not panic. Go over the theory again and talk to your teacher and other students. A different perspective can lead to a solution.

If you don't get the data you expected, don't worry. As long you can critically and objectively evaluate the investigation, identify its limitations and propose further investigations, then the work is worthwhile.

ISSUES TO CONSIDER IN SCIENTIFIC RESEARCH

Scientific research is part of human society and often has social, economic, legal and ethical implications. You need to address these implications when planning your research.

Social issues

Social issues relate to implications for individuals, communities and society. People often fear what they do not understand, so they tend to fear new scientific advances and technology.

When considering social issues, it is important to think about how technology will affect different groups of people. For example, in vitro fertilisation allows couples with fertility issues to have children. However, it is currently very expensive, meaning couples from a lower socioeconomic background may not be able to afford it.

Economic issues

All scientific research is subject to economic limitations, because all research requires money. Some research might also have important implications for local, national or global economies.

An important economic issue for scientific research relates to costs and benefits. Valuable scientific research might never be funded because it is unlikely to produce measurable benefits in the short term. For example, rare diseases usually receive less research funding than common diseases, because they affect fewer and often poorer people, and the return on an investment in research is likely to be small.

It is also important to consider who is paying for the research. For example, a company funding research into the benefits of its products will be more interested in positive results than negative results. This could result in bias when reporting the results—especially if the company reports the results, rather than the researcher.

Legal issues

The most common legal issue that researchers face is the need to obtain permits under relevant legislation. For example, in New South Wales, a legal permit is required to collect plants, trap animals or conduct any other sort of research on public land. In some parts of Australia, permission is also required from the traditional owners or custodians of land. Legal issues might also be relevant if there are risks involved in using the results of research, or when new research could lead to conflict between the people involved in the outcome.

Ethical considerations

Scientific research involving humans or animals must be approved by an ethics committee before it can commence. All research involving animals in Australia must comply with the *Australian Code of Practice for the Care and Use of Animals for Scientific Purposes*.

However, there might still be public concern about some types of research. For example, many people have raised concerns about the prospect of being able to genetically modify humans before birth, leading to 'designer babies', in which parents could choose features such as the child's sex or eye colour. The use of live animals in research (e.g. for testing the safety of pharmaceutical products) is also an issue for many people.

ETHICS APPROVAL

Ethics is a set of moral principles by which your actions can be judged as right or wrong. Every society or group of people has its own principles or rules of conduct. Scientists have to obtain approval from an ethics committee and follow ethical guidelines when conducting research that involves animals—including, and especially, humans.

If you work with animals as part of your studies, your school should have already obtained a special licence to cover this, and should be following the New South Wales Government's guidelines for the care and use of animals in schools. These guidelines recommend that schools consider the '3Rs principle':

- Replacement—replacing the use of animals with other materials and procedures where possible
- Reduction—reducing the number of animals used
- Refinement—refining techniques to reduce the impact on animals.

You should treat animals with respect and care. The welfare of the animal must be the most important factor to consider when determining the use of animals in experiments. If at any time the animal being used in your experiment is distressed or injured, the experiment must stop.

RISK ASSESSMENT

While planning for an investigation in the laboratory or outside in the field, you must consider the potential risks—for both your safety and the safety of others.

Everything we do involves some risk. **Risk assessments** identify, assess and control hazards. A risk assessment should be done for any situation that could hurt people or animals, whether in the laboratory or out in the field. Always identify the risks and control them to keep everyone safe.

To identify risks, think about:

- the activity that you will be carrying out
- where in the environment you will be working, e.g. in a laboratory, school grounds or a natural environment
- how you will use equipment, chemicals, organisms or parts of organisms that you will be handling
- the clothing you should wear.

The following hierarchy of risk control (Figure 1.2.3) is organised from the most effective risk management measures at the top of the pyramid to the least effective at the bottom of the pyramid.

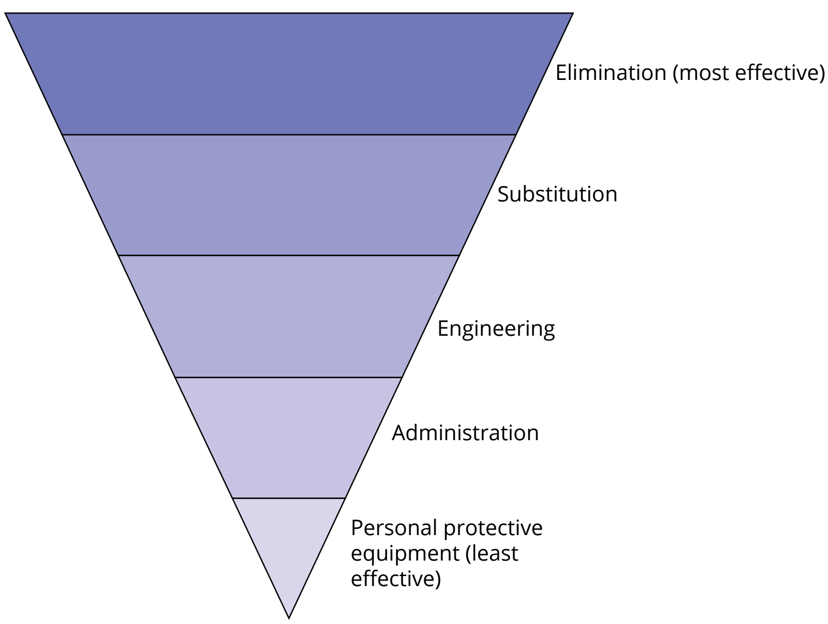

FIGURE 1.2.3 The hierarchy of risk control in this pyramid is marked from top to bottom in order of decreasing effectiveness.

Take the following steps to manage risks when planning and conducting an investigation:

- Elimination—Eliminate dangerous equipment, procedures or substances.
- Substitution—Find different equipment, procedures or substances that will achieve the same result, but have less risk.
- Engineering—Modify equipment to reduce risks. Ensure there is a barrier between the person and the hazard. Examples include physical barriers, such as guards in machines, or fume hoods when working with volatile substances.
- Administration—Provide guidelines, special procedures, warning signs and safe behaviours for any participants.
- **Personal protective equipment (PPE)**—Wear safety glasses, lab coats, gloves, respirators and any other necessary safety equipment where appropriate, and provide these to other participants.

1.2 Review

SUMMARY

- Write a protocol and schedule to plan your investigation. Test your protocol, and evaluate and modify it if necessary.
- The procedure of your investigation is a step-by-step procedure that must ensure that the investigation is valid, reliable and accurate.
- Validity refers to whether an experiment or investigation is actually testing the set hypothesis and purpose.
- Reliability or repeatability is the ability to obtain the same averaged results when an experiment is repeated.
- Controlled experiments allow us to examine only one factor at a time (the independent variable), while reducing the effects of all other variables.
- The procedure of your investigation may need to be modified during the investigation process.
- The social, economic, legal and ethical implications of scientific research must be considered when planning research.
- Social issues relate to implications for individuals, communities and society.
- Economic issues relate to costs and benefits.
- Legal issues may relate to researchers needing to obtain permits under relevant legislation.
- Scientific research involving humans or animals must be approved by an ethics committee before it can commence.
- The three Rs should be applied in any investigation that requires the use of animals:
  - Replacement—replacing the use of animals with other materials and procedures where possible
  - Reduction—reducing the number of animals used
  - Refinement—refining techniques to reduce the impact on animals.
- Risk assessments that identify, assess and control hazards should be done before undertaking laboratory or fieldwork.

KEY QUESTIONS

1. Why is it important to plan before you conduct your scientific investigation?
2. **a** Explain what is meant by the term 'controlled experiment'.
   b Using an example, distinguish between independent and dependent variables.
3. A student conducted an experiment to find out whether a bacterial species could use sucrose (cane sugar) as an energy source for growth. She already knew that these bacteria could use glucose for energy. Three components of the experiment are listed. Next to each one, indicate the type of variable described.
   a presence or absence of sucrose
   b measurement of cell density after 24 hours
   c incubation temperature, volume of culture, size of flask
4. List four issues that need to be considered when planning a scientific investigation.
5. What are the 3Rs that should be considered when using animals in research?
6. Why are risk assessments performed?

1.3 Conducting investigations

Once you have finished planning and designing your practical investigation, the next step is to undertake your investigation and record the results. As with the planning stages, you must keep key steps and skills in mind to maintain high standards and minimise potential errors throughout your investigation.

This section will focus on the best procedures for conducting a practical investigation and systematically generating, recording and processing data.

SAFE WORKING PRACTICES AND MANAGING RISKS

Personal protective equipment

FIGURE 1.3.1 A lab coat, gloves and safety glasses are essential items of personal protective equipment in the laboratory.

Everyone who works in a laboratory wears clothing and equipment to improve safety (Figure 1.3.1). This is called personal protective equipment (PPE) and includes:

- safety glasses
- shoes with covered tops
- disposable gloves for handling chemicals or organisms
- an apron or a lab coat to prevent spills from coming into contact with your clothes and skin
- ear protection if there is risk to your hearing.

Science outdoors

FIGURE 1.3.2 These botanists are well prepared for fieldwork in an alpine environment. They are wearing warm clothing, waterproof jackets, long pants and protective boots. They are carrying food, water and everything they might need in an emergency in their backpacks, and they are working in a group rather than alone.

Scientific research often involves outdoor fieldwork in potentially hazardous situations (Figure 1.3.2). Every potential risk, and ways to minimise them, must be considered when planning fieldwork. Table 1.3.1 shows some common risks associated with fieldwork and measures that can be taken to minimise them.

TABLE 1.3.1 Common risks associated with fieldwork

Risk	Measures to minimise risk
sunburn	wear a hat, sunglasses and long-sleeve top; apply sunscreen regularly
hot weather	wear light, loose-fitting clothing; drink water regularly to avoid dehydration
cold weather	wear warm clothing, such as a polar-fleece jacket and woollen hat
insect and animal bites	apply insect repellent; watch where you walk, and do not put your hand in a hole or hollow without checking it first; bring a first-aid kit
sprained ankle, blisters	wear sturdy, well-fitting boots with thick socks
wet weather	carry waterproof clothing
getting lost	work in a group, never alone; carry a map, compass, torch, GPS and mobile phone or two-way radio
bushfire	check fire conditions before you leave; do not work in the field when danger is rated high or more; carry a radio to listen for bushfire warnings

Chemical safety

Some chemicals used in laboratories are harmful. When you are working with chemicals in the laboratory or at home, it is important to keep them away from your body. Laboratory chemicals can enter the body in three ways: ingestion, inhalation and absorption.

- Ingestion—chemicals that have been ingested (eaten) may be absorbed across cells lining the mouth or enter the stomach, and may then be absorbed into the bloodstream.

- Inhalation—chemicals that are inhaled (breathed in) can cross the thin cell layer of the alveoli in the lungs and enter the bloodstream.
- Absorption—some chemicals can pass through the skin and enter the body.

When working with any type of chemical, you should:

- identify the chemical codes and be aware of the dangers they are warning about
- become familiar with chemical **Safety Data Sheets (SDS)**
- use PPE
- wipe up any spills
- wash your hands thoroughly after use.

Chemical codes

The chemicals in laboratories, supermarkets, pharmacies and hardware shops have a warning symbol on the label. These symbols are a chemical code indicating the nature of the contents (Table 1.3.2).

TABLE 1.3.2 Some of the different warning labels you might see on chemicals

Symbol	Meaning and examples	Symbol	Meaning and examples
	Biological hazards are living organisms, such as bacterial cultures, that may pose a threat of infection or irritation. To dispose of these, place in a biohazard bag ready for autoclaving (sterilisation at 121°C), or soak contaminated paper towel in ethanol or bleach. Clean contaminated surfaces with 70% ethanol or bleach.		Organic peroxides, including hydrogen peroxide, are powerful bleaching agents that cause skin and hair to turn white. They can irritate and damage skin and eyes.
	Corrosive chemicals can dissolve or eat away substances, including tissues such as your skin or airways. Examples include bleach, acids and bases (e.g. hydrochloric acid, acetic acid, sodium hydroxide), some stains used for microscopy, and biochemical reagents for detecting protein and sugars.		Irritants cause discomfort, pain or itchiness. Examples include urea, some microscopy stains and acetic acid.
	Poisons can cause injury or death if ingested, inhaled or absorbed. Examples include ninhydrin, methanol, Lugol's iodine, hydrochloric acid and formalin/formaldehyde.		Flammable liquids include alcohols, such as ethanol, acetone and glacial acetic acid.

Safety data sheets (SDS)

Every chemical substance used in a laboratory has an SDS. An SDS contains important information about how to safely handle, store and dispose of the chemical, as well as first-aid information for teachers and technicians about each chemical you commonly use in the laboratory. It also provides employers, workers and emergency crews with the necessary information to safely manage the risk of hazardous substance exposure.

An SDS states:

- the name of the hazardous substance
- the chemical and generic names of certain ingredients
- the chemical and physical properties of the hazardous substance

- health hazard information
- how to store the chemical safely
- precautions for safe use and handling
- how to dispose of the chemical safely
- the name of the manufacturer or importer, including an Australian address and telephone number.

First aid

Minimising the risk of injury reduces the chance of requiring first-aid assistance. However, it is still important to have someone with first-aid training with you during practical investigations. Always tell your teacher or laboratory technician if an injury or accident happens.

RESEARCH TECHNIQUES

Many research techniques are used in scientific investigations. Throughout your studies, you may be required to undertake investigations through a combination of laboratory work and fieldwork.

Laboratory work

Techniques that you may use in a biology laboratory include:

- microscopy—to observe cells, tissues and microscopic organisms (Figure 1.3.3). You'll learn more about microscopy in Chapter 2.
- cell and **tissue culture**—growing cells and tissues to investigate their growth rates, responses and other biological processes (Table 1.3.3)
- investigating biochemical processes, such as cellular respiration and photosynthesis. You'll learn more about these processes in Chapter 3.
- investigating enzymatic reactions. Enzymes are covered in detail in Chapter 3.

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TABLE 1.3.3 Growing cells for biology investigations

	Bacteria and yeast are cultured in appropriate liquid nutrient broth or nutrient agar plates.
	Algae and protists can be grown in suitable protist medium in sterile glassware. Algae are grown in good light conditions. Protists prefer the dark.
	In plant tissue culture, small segments of stem or leaf are surface sterilised to remove contaminants. Cells or tissues of plants are cultured on nutrient agar over days or weeks.

FIGURE 1.3.3 *Paramecium caudatum* viewed under a light microscope. *Paramecium* is a large unicellular protist that is commonly used as a model organism in classrooms and laboratories.

- spectrophotometry or colorimetry—to measure light absorbance to quantify biological reactions (Table 1.3.4, Figure 1.3.4)
- chromatography—to investigate pigments and other biological products (Figure 1.3.5)
- electrophoresis—to separate proteins and DNA by size, and investigate DNA fragments amplified using the **polymerase chain reaction (PCR)** (Figure 1.3.6)
- PCR—to make many copies of sections of DNA for sequencing
- DNA sequencing and analysis—to understand the inheritance of traits, the function of genes and the genetic diversity and structure of populations. You'll learn more about the use of biochemical data in Chapter 10.
- immunology—to investigate human responses to invading pathogens and disease.

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Tools to support your practical investigations

Table 1.3.4 lists some tools you might use during your investigations.

TABLE 1.3.4 Tools that can be used in practical investigations

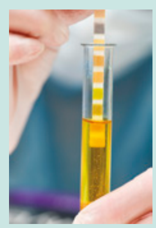
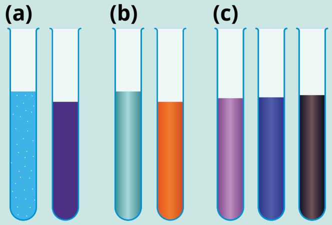
Simple indicator of pH	Measuring pH or temperature	Measuring solutes
Tool: a dipstick test for the full pH range. A strip with pH-sensitive coloured pads is dipped into a solution, and then read against a reference colour chart after a defined time. **Purpose:** to measure the pH of a solution.	**Tool:** electronic meters and probes. **Purpose:** to measure pH or temperature.	**Tool:** strip tests for measuring glucose, protein and other solutes: • Multistix® tests for several substances • UriScan® tests glucose and protein • Glucostix® tests glucose only **Purpose:** usually designed for urine testing. Coloured pads on the strip are dipped into urine or other solutions; the colour develops and is read against a reference chart. Detection is often based on an enzyme reaction within the pad.
		
Data loggers for a range of measurements	**Biochemical/chemical tests to detect molecules**	**Measuring absorbance, optical density or turbidity**
Tools: common types of probes and capabilities in data loggers include: • pH • temperature • oxygen concentration • carbon dioxide concentration • absorption colorimeter • concentration of various compounds. **Purpose:** data loggers enable data collection over long periods.	**Tools include:** **a** biuret reagent* for detecting protein (purple) **b** Benedict's reagent* for detecting reducing sugars, such as glucose, maltose, fructose; not sucrose (red) **c** iodine–potassium iodide (IKI)* reagent for detecting starch (blue/purple). **Purpose:** to detect different biochemical reactions.	**Tool:** colorimeter or spectrophotometer. **Purpose:** to quantitate colour reactions, or measure turbidity for monitoring cell growth.
	(a) (b) (c) 	
	* Some tests are qualitative; quantitative or semi-quantitative results may be achieved if combined with standards and absorbance readings.	

FIGURE 1.3.5 Thin-layer chromatography (TLC) plate in a beaker, showing separated components (colours). TLC is performed on a sheet of glass, plastic or foil coated in a thin layer of adsorbent material.

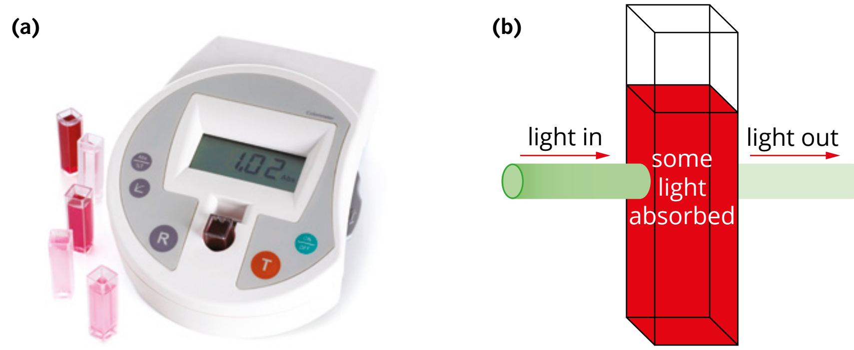


FIGURE 1.3.4 A colorimeter or spectrophotometer (a) reads absorbance of light. A sample is placed in a cuvette and placed in the instrument. Light of a particular wavelength is shone through the sample (b). The meter reads the amount of light absorbed by the sample. A sample with higher concentration gives a higher absorbance reading.

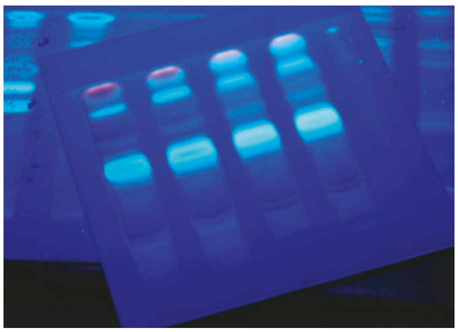


FIGURE 1.3.6 Gel electrophoresis uses an electric current to separate fragments of protein and DNA. Fragments of different sizes separate as they travel through the gel, because smaller fragments travel faster than larger fragments.

Fieldwork

Biological investigations often include fieldwork. For example, you may want to determine the type and number of living organisms in an area. There are many different ways to do this, including quadrats and transects. Whatever way you use, it is important to always leave the environment the way you found it (Figure 1.3.7).

FIGURE 1.3.7 When working in the field, a good principle to work by is: take only photographs, leave only footprints.

In natural environments, it is usually impossible to count all the individuals of a species. Even just counting the living things in your school would take a very long time. Sampling gives us a good idea of the organisms in an ecosystem without needing to count each one.

When sampling in the field, you should always consider the time and equipment available, the organisms involved and the impact the sampling may have on the environment.

Some common sampling techniques used to investigate species in the field are:

- **point sampling**—counting organisms at selected points
- **quadrats**—a square, rectangular or circular area that is surveyed as a representative of a larger area
- **transects**—a straight line along which vegetation is sampled
- water sampling—water is collected in a container and organisms are counted
- **mark–recapture**—animals are captured, marked and then released. When animals are observed or recaptured, their mark is used to identify them.

Chapter 11 outlines these sampling techniques in more detail, and describes when they are best used in the field.

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IDENTIFYING AND REDUCING ERRORS

When an instrument is used to measure a physical quantity and obtain a numerical value, the aim is to determine the true value. However, the measured value is often not the true value. The difference between the true value and the measured value is called the **error**. This error in the measured value is the result of errors in the experiment, and can be one of two main types: systematic errors and random errors.

Systematic errors

A **systematic error** (or bias) is a consistent error that occurs every time you take a measurement. Systematic errors are not easy to spot, because they do not appear as a single difference in the dataset. Instead, repeated measurements give results that differ by the same amount from the true value. There are many different types of systematic errors, but the most common types are selection bias and **measurement bias**.

Selection bias

Selection bias occurs when your sample is not representative of the population being studied. This can have several different causes, including sampling bias and time-interval bias. Sampling bias occurs when your sample has not been selected randomly. Time-interval bias occurs when you stop your study too early, because you think the results support your hypothesis.

Measurement bias

Measurement bias is usually a result of instruments that are faulty or not calibrated, or the incorrect use of instruments. Both of these produce inaccurate results. For example, if a scale under-reads by 1%, a measurement of 99 mm will actually be 100 mm. Another example would be if you repeatedly used a piece of equipment incorrectly throughout your investigation, such as reading from the top of the **meniscus** instead of the bottom when using a measuring cylinder or graduated pipette (Figure 1.3.8).

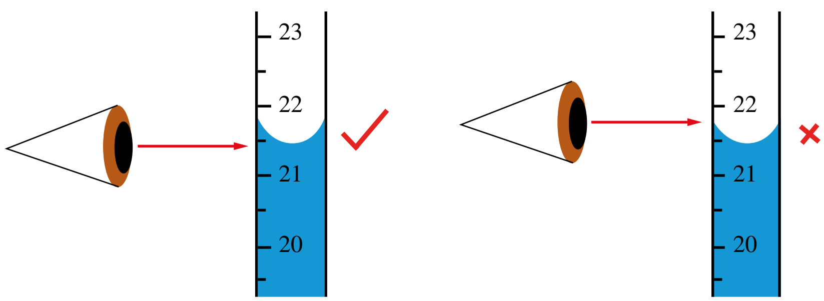

FIGURE 1.3.8 When measuring liquid levels in cylinders and pipettes, measure the value at the bottom of the meniscus of the liquid, as shown in (a), not at the top, as shown in (b).

A meniscus is the curved upper surface of liquid in a tube.

Reducing systematic errors

The appropriate selection and correct use of **calibrated** equipment will help you reduce systematic errors. Because systematic errors are difficult to identify, it is also a good idea (if you have time) to repeat your measurements using different equipment.

Appropriate equipment

Use equipment that is best suited to the data you need to collect. Determining the units and scale of the data you are collecting will help you to select the correct equipment. For example, if you need to measure 10 mL of a liquid, using a 10 mL graduated pipette or a 20 mL measuring cylinder will give more accurate readings than when using a 200 mL measuring cylinder, because the pipette or smaller cylinder will have a finer scale.

Calibrated equipment

FIGURE 1.3.9 A student measures the pH level of tartaric acid using a pH meter. To ensure an accurate reading, the student would first have calibrated the meter using standard solutions of known pH.

Accurate measurement requires properly calibrated equipment. Before you carry out your investigation, make sure your instruments or measuring devices are properly calibrated and functioning correctly (Figure 1.3.9). Your school laboratory may have a set of standard masses that can be used to calibrate a balance or scale. A pH meter should have a set of standard pH solutions (e.g. at pH 4, pH 7 and pH 9) that you can use to check the meter readings and adjust the meter if necessary.

Correct use of equipment

Make sure you have been trained to use equipment correctly. Write the instructions in detail so you can follow them exactly each time, and practise using the equipment before you start your investigation. Improper use of equipment can result in inaccurate, imprecise data with large errors, which compromises the validity of the data. An example of incorrect use of a balance would be if it was not placed on a level surface, or if it was used in a room with strong air currents or vibrations.

Random errors

Random errors (also called variability) are unpredictable variations that can occur with each measurement. Random errors can occur because instruments are affected by small variations in their surroundings, such as changes in temperature. All instruments have a limited precision, so the results they produce will always fall within a range of values.

Reducing random errors

To reduce random errors, you need to take more measurements or increase your sample size. You can then calculate the average (the mean), which is a more accurate representation of the data.

More measurements

The impact of random errors can be minimised by taking more measurements and then calculating the average value. In general, more measurements will improve the accuracy of the measured value. The minimum number of measurements you should take is three, but you may need more depending on the type of investigation you are conducting. If one reading differs greatly from the rest, mention this in your results and discuss possible reasons for the difference. If you think it is the result of an error, do not include it in your results, because it will skew (bias) the result.

Sample size

Increasing the **sample size** reduces the effect of random errors, which in turn makes your data more reliable. For example, if you are investigating the effects of light intensity on the rate of photosynthesis in *Elodea* (a genus of aquatic plants), do not test your hypothesis on just one stem. Test several stems (minimum three). If two stems photosynthesise and one does not, it is reasonable to conclude that one stem was unhealthy or the conditions incorrect. Using a large number of samples will reduce the likelihood of your results being skewed.

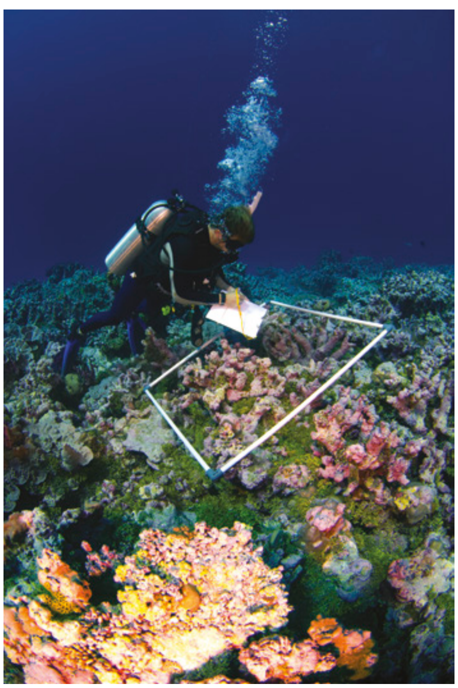

FIGURE 1.3.10 This marine biologist is keeping a logbook, recording observations of each coral in the square quadrat.

DATA COLLECTION

The measurements or observations that you collect during your own investigation are your primary data (Figure 1.3.10). Keep in mind that different types of data can be collected in a scientific investigation. When planning your investigation, you should consider the type of data you will collect and how best to record it. Data can be raw or processed, and qualitative or quantitative.

Keeping a logbook

During your investigation, you must keep a logbook that includes every detail of your research. The following checklist will help you remember to record:

- your ideas when planning your investigation
- clear protocols for each stage of your investigation (e.g. what standard procedures you will use)
- all materials, procedures, experiments and raw data
- instructions or tables noting exactly what needs to be recorded
- experimental/observation protocols that you will follow exactly each time
- tables you draw up ready for data entry (see Table 1.3.5)
- all notes, sketches, photographs and results (directly into logbook—not on loose paper)
- any incidents or errors that may influence results.

Raw and processed data

The data you record in your logbook is **raw data**. This data often needs to be processed or analysed before it can be presented. If an error occurs in processing the data, or you decide to present the data in a different format, you will always have the recorded raw data to refer back to.

Raw data is unlikely to be used directly to validate your hypothesis. However, it is essential to your investigation, and plans for collecting your raw data should be made carefully. Consider the formulas or graphs you will be using to analyse your data at the end of your investigation. This will help you to determine the type of raw data you need to collect to test your hypothesis.

For example, you might want to study the effect of nutrient concentration on tomato production in a hydroponic garden. To do this, you might collect two sets of raw data: the concentration of nutrient solution applied to each plant, and the total mass of tomatoes harvested from each plant. Once you have determined the data you need to collect, prepare a table to record it (e.g. Table 1.3.5).

You can then process this data further. For example, the nutrient might be very expensive, so you might be interested in the ratio of tomato mass to nutrient concentration. This value (shown in the last column in Table 1.3.5) is **processed data**. Processed data is obtained by applying a calculation or formula to raw data.

Primary data is data that you collect yourself. Secondary data is data that someone else has collected.

TABLE 1.3.5 An example of the kind of table used in a logbook for primary (raw) data collection

Plant tray no.	Total tomato mass (kg)	Nutrient concentration (g/L)	Mass per unit concentration (kg per g/L)
1	1.25	5.0	0.250
2	2.81	10.0	0.281
3	4.64	15.0	0.309
4	5.02	20.0	0.251
5	5.84	25.0	0.234

SOURCING INFORMATION

You might source information to learn more about your research topic, prepare a literature review, research experimental procedures or investigate a broader issue. Every time you source information, consider whether it comes from primary or secondary sources. You should also consider the advantages and disadvantages of using resources such as books or the internet.

Primary and secondary sources

Primary and secondary sources provide valuable information for research. Primary sources of information are from investigations that you have conducted yourself, while secondary sources are information from investigations that have been conducted by others. Table 1.3.6 compares primary and secondary sources.

TABLE 1.3.6 Summary of primary and secondary sources of information

	Primary sources	Secondary sources
Characteristics	• first-hand records of events or experiences • written at the time the event happened • original documents	• interpretations of primary sources • written by people who did not see or experience the event • reworked information from original documents
Examples	• results from your experiments • reports of your scientific discoveries • photographs, specimens, maps and artefacts that you collected	• textbooks • scientific journal/magazine articles • biographies • newspaper articles • magazine articles • documentaries • interviews with experts • websites that interpret the scientific work of others

FIGURE 1.3.11 You will find reputable science magazines in your school library.

Using books and the internet

The resources you use affect the quality of your research. **Peer-reviewed** scientific journals are the best sources of information, but some are only accessible with a subscription. Books, magazines and internet searches will be your most commonly used resources for information. However, you should be aware of the limitations of these resources (Table 1.3.7). Reputable science magazines you might find in your school library include *New Scientist*, *Cosmos*, *Scientific American* and *Double Helix* (Figure 1.3.11).

TABLE 1.3.7 Advantages and disadvantages of book and internet resources

	Book resources	Internet resources
Advantages	• written by experts • authoritative information • have been proofread, so information is usually accurate • logical, organised layout • content is relevant to the topic • contain a table of contents and index to help you find relevant information	• quick and easy to access • allow access to hard-to-find information • access to information from around the world; millions of websites • up-to-date information
Disadvantages	• may not have been published recently—information may be outdated	• time-consuming looking for relevant information • a lot of 'junk' sites and biased material • search engines may not display the most useful sites • cannot always tell if information is up to date • difficult to tell if information is accurate • hard to tell who has responsibility for authorship • information is not ordered • less than 10% of sites are educational

Secondary sources of information include books, journals, magazines, newspapers, interviews, television programs and the internet. You should aim to use a wide range of data sources when performing your secondary-sourced investigations. Secondary sources may have a bias, so you need to determine if they are accurate, reliable and valid sources of information. You will learn about assessing the accuracy, reliability and validity of secondary data in Section 1.5.

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Biological databases

Many open-access **databases** of biological information are available on the internet. They include databases of gene and protein sequences, biochemical pathways and cellular signalling. Other open-access databases provide a large body of information for investigating the living world, biosciences and molecular biology. They include databases from museums and research institutions, and include the records of specimens, fauna and flora, biodiversity and fossil collections (Table 1.3.8). They may include images, raw data and geographic distributions of species that can be compared when investigating biological change and continuity over time (Figure 1.3.12).

TABLE 1.3.8 Useful databases for investigating biological diversity

Examples of biological databases	Type of data, information or applications
Encyclopedia of Life World Register of Marine Species Atlas of Living Australia	species information, biodiversity, taxonomy, phylogeny
Museums Victoria	species data, classification, geographic distribution over time, skull image databases, biological data, fossils
Australian Museum—Learning Resources	evolution and extinction of Australian mammals; human evolution with 3D virtual skulls
American Museum of Natural History Smithsonian Museum of Natural History	research and collections with links to various resources, e.g. palaeobiology, bioinformatics
The Paleobiology Database Fossilworks	databases of fossils, geographic distributions, timescales, analysis tools, maps

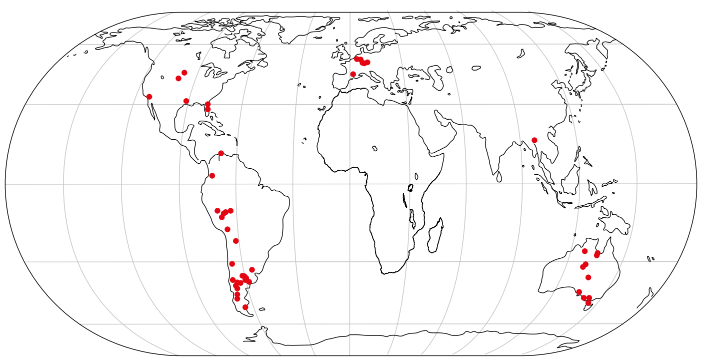

FIGURE 1.3.12 This map shows the distribution of marsupials in the Miocene geological period. It was constructed using a palaeontology database with search and mapping tools.

Referencing secondary-sourced information

As you conduct your investigation, it is important to make note of any secondary-sourced information that you use. This will then be included in your written report. You will learn more about writing scientific reports and referencing in Section 1.7.

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Categorising the information and evidence you find while you are researching will make it easier to locate information later and to write your final report. Categories you might use while researching could include:

- research procedures
- key findings
- evidence
- relevance to your research
- issues to consider (e.g. social or ethical issues)
- people affected by the research
- future concerns.

Record information from resources in a clear way so you can retrieve and use it later.

1.3 Review

SUMMARY

- Everyone who works in a laboratory wears personal protective equipment (PPE), such as safety glasses, disposable gloves and a lab coat.
- Laboratory chemicals can enter the body in three ways:
  - ingestion
  - inhalation
  - absorption.
- Chemical codes indicate the nature of the contents of solutions, powders and other reagents that are used in the laboratory (e.g. flammable, corrosive, poisonous).
- Every chemical substance used in a laboratory has a safety data sheet (SDS).
- Many different techniques are used in the laboratory, such as microscopy, cell culture and DNA sequencing.
- Many different techniques are used in the field, such as point sampling, mark–recapture, transects, quadrats and water sampling.
- Reduce random errors by:
  - having a large sample size
  - repeating measurements.
- Reduce systematic errors by:
  - selecting appropriate equipment
  - properly calibrating equipment
  - using equipment correctly
  - repeating experiments.
- Record all information objectively in your logbook, including your data and procedures.
- Raw data is the data you collect in your logbook.
- Processed data is raw data that has been mathematically manipulated.
- Primary sources of information are first-hand records of investigations that you conducted yourself.
- Secondary sources of information are records of primary sources conducted or written about by someone else, such as a scientific journal or magazine article.

KEY QUESTIONS

1 Explain the difference between ingestion, inhalation and absorption.

2 What does SDS stand for? Explain the reasons for having an SDS for each of the chemicals used in the laboratory.

3 If you spilled a chemical substance with the following label on yourself, what would be the appropriate thing to do?

4 Suggest some procedures you could use for detecting carbon dioxide generation during respiration in yeast, water plants or algae.

5 Which materials or procedure(s) from the list below could you use for the experiments listed in the following table? Copy and complete the table by writing the letter(s) into the right-hand column.

A biochemical test
B bacterial culture
C glucose test strip
D pH meter, indicator or pH stick
E data logger—temperature probe
F plant tissue culture
G data logger—oxygen probe
H staining and microscopy
I spectrophotometer/colorimeter

	Materials or procedure(s)
i measure oxygen released in photosynthesis	
ii test the effectiveness of antibiotics on the rate of bacterial growth	
iii quantitatively measure protein concentration in an enzymatic reaction	
iv identify phagocytosis in ciliate protozoa	
v measure glucose in an enzyme experiment	

6 Two sets of data are given below. Both sets contain errors. Identify which set is more likely to contain a systematic error and which is more likely to contain a random error.
Dataset A: 11.4, 10.9, 11.8, 10.6, 1.5, 11.1
Dataset B: 25, 27, 22, 26, 28, 23, 25, 27

7 What is the difference between raw and processed data?

8 Decide whether each of the following is a primary or a secondary source of information.

a a newspaper article about genetically modified human embryos
b an experiment to investigate molecular changes within cells treated with hormones
c an interview with a fisheries molecular scientist about using DNA analysis for tracking tiger sharks
d a website with information about genetic engineering

1.4 Processing data and information

Once you have conducted your investigation and collected data, you will need to find the best way of collating it. This section is a guide to the different forms of representation that will help you to better understand your data.

QUALITATIVE AND QUANTITATIVE DATA

Qualitative data

Data collected about categorical variables is **qualitative data**. Categorical variables can be counted, but not measured. They relate to a type or category, such as colour or gender; or to states, such as on/off or wet/dry. Categorical variables can be nominal or ordinal.

- Nominal (or unordered) variables are categorical variables that have no inherent order; they can be counted, but not ordered. Examples are flower colour, gender, number of children or breed of dog.
- Ordinal (or ordered) variables are categorical variables that have an inherent order. They have a ranking or level, so they can be counted and also ordered. Examples are age group, position in a DNA sequence or trophic level.

Recording qualitative data

Qualitative data can be represented by names, symbols or numbers. Observations of categorical variables can be descriptions or images. For example, dog breeds could be shown in a diagram, or textures of materials could be described using words such as brittle, coarse, crumbly, dense, flexible, rocky, rough, silky, slimy, smooth, spongy or velvety.

When you have to record qualitative data, think carefully about how to define each categorical variable. For example, if you are recording colours, a set of reference colours is a good way of clearly showing what each colour represents (Figure 1.4.1).

FIGURE 1.4.1 When recording the colour of leaves, a reference image like this one helps you record good qualitative data.

Creating a referencing system, such as assigning codes to different colours, allows you to quickly and easily record your data. For example, for the different colours in Figure 1.4.1, you could use codes named G1, G2 and G3 for different shades of green, Y1, Y2 and Y3 for different shades of yellow, and O1, O2 and O3 for different shades of orange. You might find that someone has already created a coding system for the data you want to collect, so it is a good idea to check before making your own. Whatever system you choose, make sure you apply it consistently.

Quantitative data

Data collected about numeric variables is **quantitative data**. Like categorical variables, numeric variables can be counted. Unlike categorical variables, numeric variables can also be measured, because they have a measurable quantity, such as length, mass or time. Numeric variables can be discrete or continuous.

- Discrete variables are values that can be counted or measured, but that can only have certain values. Examples are the number of fish in a pond, the number of red blood cells on a slide, or the number of times a lever is pulled.
- Continuous variables may be any number value within a given range that can be measured. Examples are age, temperature, length, mass and wavelength.

Recording quantitative data

When you record quantitative data, remember to use scientific measuring units such as grams, centimetres, millimetres or degrees Celsius. Table 1.4.1 summarises the different types of data and variables.

TABLE 1.4.1 Summary of types of data and variables

Data type	Variable	Variable types	Examples
qualitative	categorical	nominal (no inherent category order)	object colour, biological sex
		ordinal (inherent category order)	age group, light intensity, house number
quantitative	numeric	discrete (distinct and separate values)	number of stars in the galaxy, number of flowers in the garden
		continuous (any number value in a range)	temperature, time, height, age

DESCRIPTIVE STATISTICS

Descriptive statistics can be used for both quantitative and qualitative data. An important type of descriptive statistic is the **measure of central tendency**. It is good practice to use a measure of central tendency to provide a clearer understanding of the data.

Measures of central tendency

Measures of central tendency are single values that allow you to describe the central position in a set of data. Measures of central tendency are sometimes also called measures of central location. Examples include the mean, median and mode.

The **mean** (or average) is the sum of the values divided by the number of values. For example, the mean of 3, 7, 9, 10 and 11 is (3 + 7 + 9 + 10 + 11) ÷ 5, which is 8.

The **median** is the 'middle' value in an ordered list of values. For example, the median of the seven values 5, 5, 8, 8, 9, 10 and 20 is the fourth value, which is 8.

The **mode** is the value that occurs most often in a list of values. This measure is particularly useful for describing qualitative or discrete data. For example, the mode of the values 0.01, 0.01, 0.02, 0.02, 0.02, 0.03 and 0.04 is 0.02.

The appropriate measure of central tendency to use depends on the type of data you are working with (Table 1.4.2).

TABLE 1.4.2 The most appropriate measures of central tendency to use in descriptive statistics depends on the type of data.

Type of data	Mode	Median	Mean
nominal (qualitative)	✓	✗	✗
ordinal (qualitative)	✓	✓	maybe
discrete or continuous (quantitative)	✓	✓	✓

SUMMARISING DATA

Most of the time, you will want to summarise your data so that you can generalise your sample results to a population. For example, if you were testing the effects of fertiliser on the growth of bean plants, you would probably want to generalise your results to the growth of bean plants generally, not just the bean plants you used in your experiment. To provide a bigger picture, you can do some further calculations on the data.

Percentage change

Calculating the change in a variable is a helpful statistic, because it provides a general trend or pattern, rather than a specific value that may vary depending on size or shape, for example. Table 1.4.3 shows the data collected over five days for three plants. One plant was a control, the second was exposed to intense light, and the third plant was in low light.

TABLE 1.4.3 Percentage change in plant mass for different light intensities over five days

Plant	Mass on day 1 (g)	Mass on day 2 (g)	% change	Mass on day 3 (g)	% change	Mass on day 4 (g)	% change	Mass on day 5 (g)	% change
Plant 1 (control)	12.3	12.5	1.63	12.7	1.60	12.8	0.79	13.0	1.56
Plant 2 (intense light)	12.4	12.7	2.42	13.0	2.36	13.4	3.08	13.7	2.24
Plant 3 (low light)	12.1	12.0	−0.83	11.8	−1.67	11.9	0.85	11.8	−0.84

The mass of each plant was measured at the same time each day. The percentage change in mass was calculated from day 2 onwards.

$$\text{percentage change} = \left(\frac{\text{day 2 mass} - \text{day 1 mass}}{\text{day 1 mass}}\right) \times 100$$

The percentage change (loss or gain) values can then be graphed for each plant.

Percentage difference

The percentage difference (also often expressed as a fraction) is a measure of the precision of two measurements. It is calculated by working out the difference between the two measurements and dividing by the average of the two measurements:

$$\text{percentage difference} = \left(\frac{\text{measurement 1} - \text{measurement 2}}{\text{average of measurement}}\right)$$

For example, if two measurements were 25 cm and 24 cm, you would calculate percentage difference as follows:

$$\text{percentage difference} = \frac{(25-24)}{(25+24)\div 2} = \frac{1}{24.5} = 0.041 \times 100 = 4.1\%$$

Calculating uncertainty in measurement

When averaging repeat measurements, you should report the **uncertainty** alongside your average. Uncertainty results from errors and represents a realistic range within which the true value is likely to be. A simple way to calculate the uncertainty is:

$$\text{uncertainty} = \pm(\text{maximum value} - \text{minimum value}) \div 2$$

For example, if an experiment was conducted to measure the length of time it takes to convert a substrate to a product in an enzymatic reaction, and three replications of the experiment produced the times 2.50, 3.47 and 2.81 seconds, the average time taken would be 2.93 seconds. The uncertainty would be calculated as follows:

$$\text{uncertainty} = \pm(3.47 - 2.50) \div 2 = \pm 0.49$$

Therefore the results showing the mean and uncertainty would be 2.93 = ±0.49.

Calculating the range of measurements

The **range** is simply the difference between the highest and lowest values in your dataset. Table 1.4.4 shows the measurements taken for eight different white bolly gum leaves.

TABLE 1.4.4 Width of white bolly gum leaves

Leaf no.	1	2	3	4	5	6	7	8
Width (cm)	7.6	9.1	9.3	10.1	5.6	10.3	9.4	8.5

To determine the range for values in Table 1.4.4, you would subtract the smallest value (5.6 cm) from the largest value (10.3 cm), which equals 4.7 cm. Notice how a very large or small value in the dataset makes the variability appear high. For example, if the small leaf with a width of 5.6 cm had not been included, the range would have only been 2.7 cm. This illustrates the importance of having a sample size that is large enough to limit the impact of anomalies (the odd ones out) in the dataset. These are also known as **outliers**.

PRESENTING DATA

After you have completed your experiment, the data need to be organised and displayed. This makes it much easier to identify trends or patterns in the data. It also helps to identify any relationships that result from cause and effect between the independent and dependent variables. This can help you see if one variable has had any effect on another variable.

You can present data in many ways, including tables, graphs, flow charts or diagrams. The best way of visualising your data depends on its nature. Try several formats before you make a final decision to create the best possible presentation.

Presenting data in tables

Tables record number values and allow you to organise your data.

Presenting raw data in tables

Tables organise data into rows and columns, and can vary in complexity according to the nature of your data. They can be used to organise raw data and processed data, or to summarise results.

The simplest form of a table is a two-column chart. The first column should contain the independent variable (the one you change) and the second column should contain the dependent variable (the one that may change in response to a change in the independent variable).

As you can see in Figure 1.4.2, tables should have:

- a descriptive title
- column headings (including the units)
- aligned figures (align the decimal points)
- the independent variable placed in the left column
- the dependent variable placed in the right column.

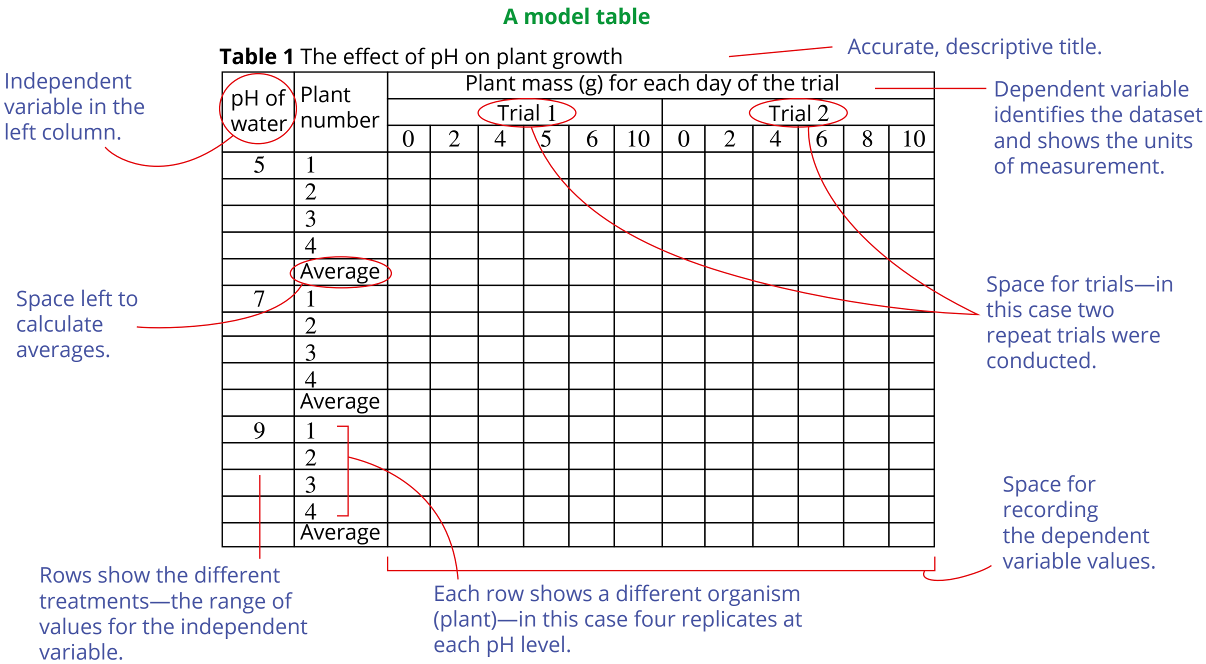


FIGURE 1.4.2 Features of a good table

Presenting processed data in tables

Table 1.4.5 shows the relationship between temperature and mean transpiration rate. It displays transpiration data in a processed format, because several values have been averaged to calculate the mean.

TABLE 1.4.5 Effect of temperature on mean transpiration rate

Temperature (°C)	Mean transpiration rate (mL/g/h)
15	0.038
25	0.043
35	0.059
45	0.074

Table 1.4.6 is an improved version of the data in Table 1.4.5, because it includes the uncertainty in the processed data.

TABLE 1.4.6 Effect of temperature on mean transpiration rate, including uncertainty

Temperature (°C)	Mean transpiration rate (mL/g/h)
15	0.038 ± 0.002
25	0.043 ± 0.001
35	0.059 ± 0.001
45	0.074 ± 0.0015

Presenting data in graphs

In general, tables provide more detailed data than graphs. However, it is easier to observe trends and patterns in data in graph form than in table form. Graphs are used when two variables are being considered, and one variable is dependent on the other (Figure 1.4.3).

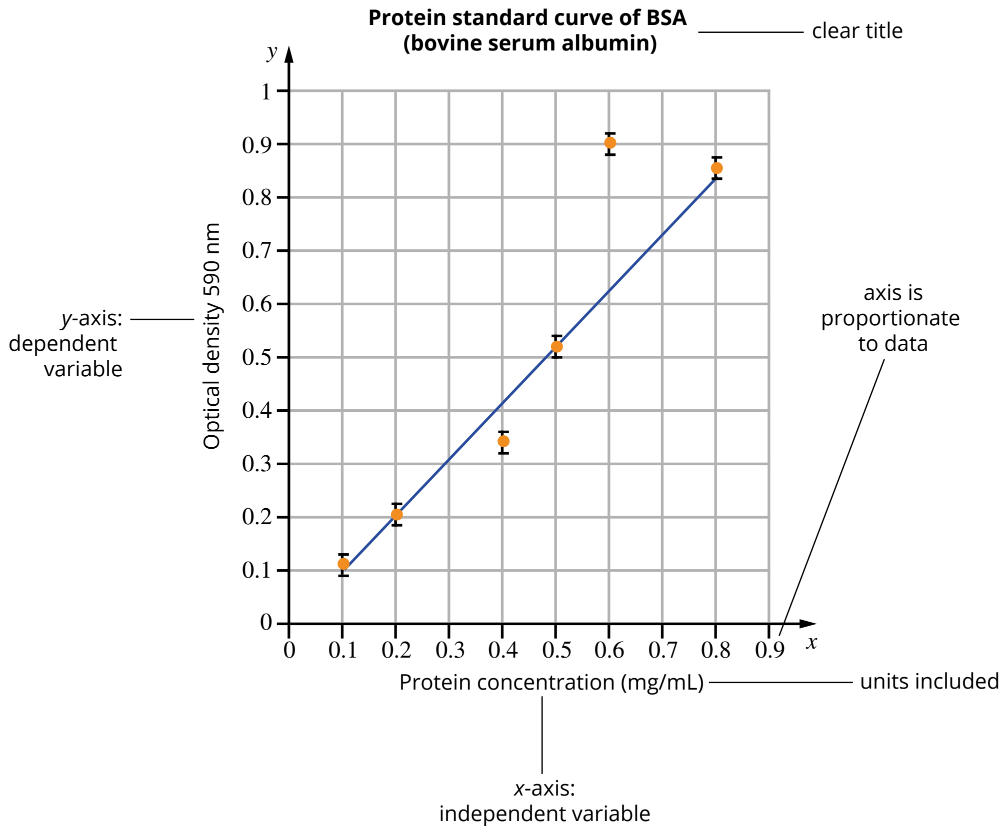


FIGURE 1.4.3 This graph shows the relationship between two variables: protein concentration (independent variable) and optical density at 590 nm (dependent variable).

Types of graphs include line graphs, bar graphs and pie charts. The best one to use will depend on the nature of the data. The following checklist contains general rules to follow when making a graph.

- Keep the graph simple and uncluttered.
- Use a descriptive title.
- Represent the independent variable on the *x*-axis and the dependent variable on the *y*-axis.
- Start each axis at zero.
- Ensure the range of each dataset can fit on each axis by selecting appropriate intervals (e.g. for a dataset of 0–100, intervals of 10 are more appropriate than intervals of 0.1).
- Clearly label axes with both the variable and the unit in which it is measured.
- Use small symbols such as circles or squares for data points.
- Use different symbols for different datasets.

Scatterplots and line graphs

Scatterplots are commonly used to display data in the form of a graph. They are used to show the relationship between two variables when one variable is dependent on the other.

The independent variable, which is set by the experimenter, is always shown on the *x*-axis. The dependent variable, which is the variable measured in the experiment, is always shown on the *y*-axis. The data is plotted on the graph as a series of points.

Each point should be drawn in pencil as a small circle or cross. Alternatively, you can use a computer program to generate graphs.

A **line graph** is a good way to represent continuous, quantitative data. In a line graph, the values are plotted as a series of points on the graph. A line can then be drawn from each point to the next, as shown in Figure 1.4.4. This line shows the change in data from one point to the next, but does not predict the value of a point between the plotted data.

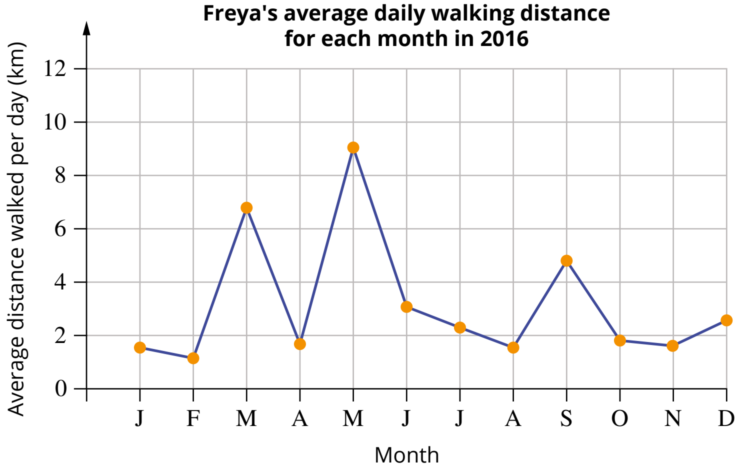


FIGURE 1.4.4 This line graph shows the average daily walking distance of a student for each month in 2016, with lines ruled from each point to the next.

Alternatively, a single straight or curved line can be drawn, as shown in Figure 1.4.5. This line is called a **trend line** or a **line of best fit**. It is used to show the overall trend in the data, and can be used to predict values between data points. A line of best fit does not usually pass through every data point. Its position can be estimated by eye, but for more accurate results, the line of best fit is calculated mathematically from the data.

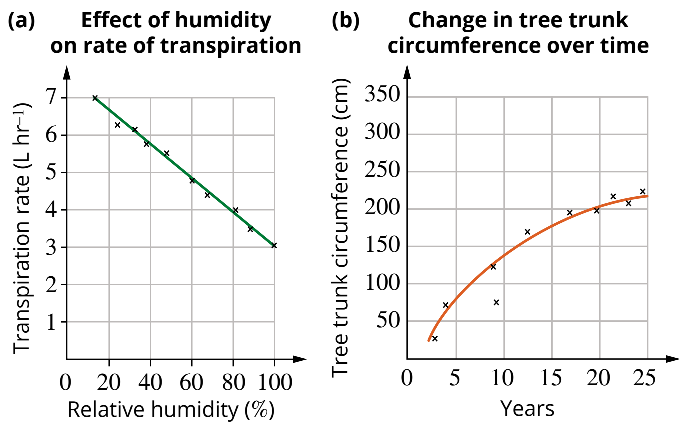


FIGURE 1.4.5 These two graphs show straight (a) and curved (b) trend lines.

Bar and column graphs

Bar and column graphs are used to show categories of data that have been counted.

- A **column graph** shows the value of the dependent variable by the height of the column; the categories are labelled across the *x*-axis.
- A **bar graph** shows the value of the dependent variable by the length of the horizontal bar; the categories are labelled up the *y*-axis.

Bar and column graphs are commonly used when the independent variable is categorical rather than numerical. The bars or columns are always the same width and the same distance apart.

Bar and column graphs are very useful for graphing qualitative and discontinuous data, such as the number of base pairs and genes on each human chromosome (Figure 1.4.6).

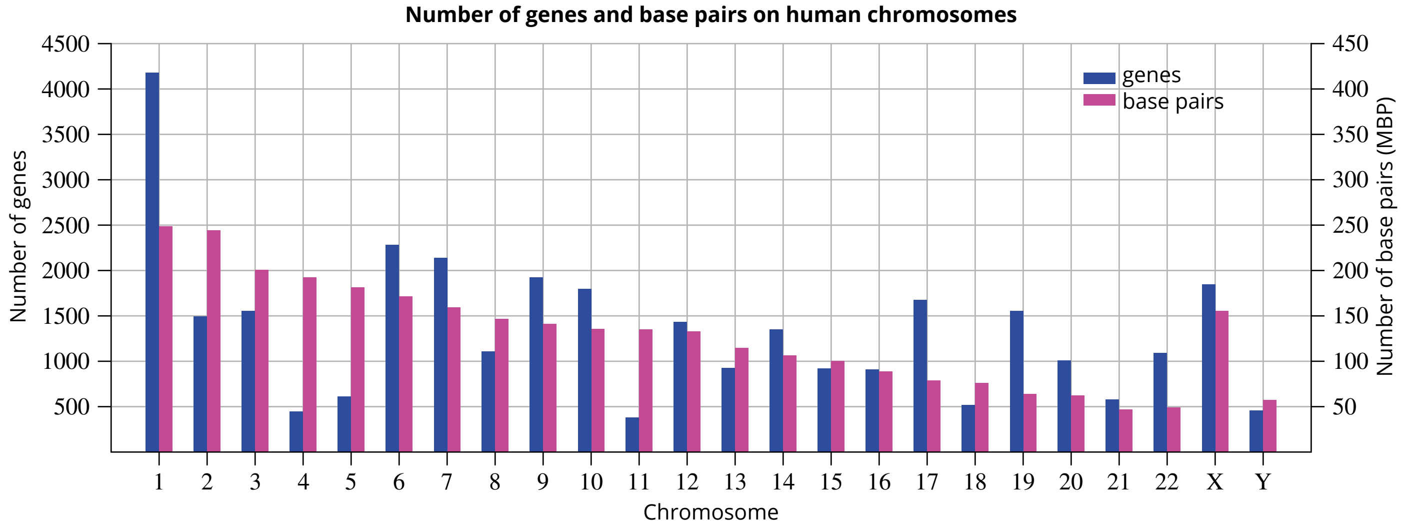


FIGURE 1.4.6 This column graph compares the number of genes (blue, left axis) and the number of base pairs (pink, right axis) on human chromosomes. Note that two different vertical axes are used for the different datasets, very different scales.

When the labels of the variables are long, horizontal bar graphs can be used. Bar graphs are also used when the data ranges are variable and overlapping, such as genome sizes (Figure 1.4.7).

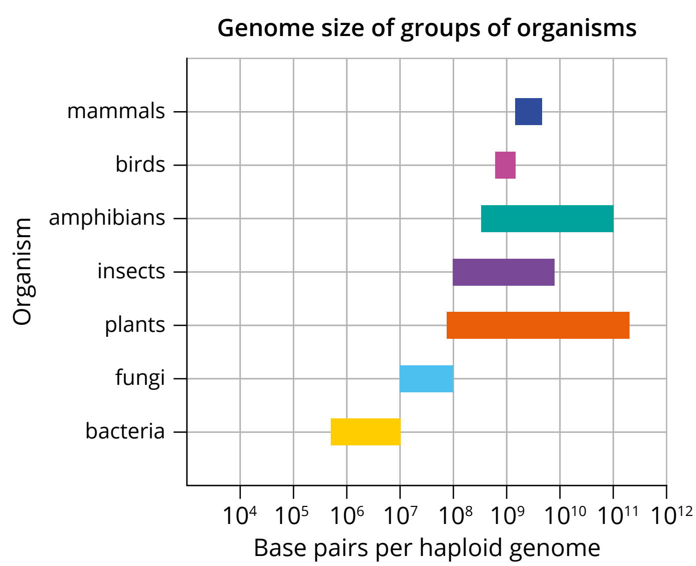


FIGURE 1.4.7 This horizontal bar graph compares the genome size of organisms from different groups of life.

Pie charts

A **pie chart** is a way of presenting qualitative data. It shows each category of data as a proportion of the total data. The chart is a circle divided into sections according to the proportions of each category, like slices of a pie (Figure 1.4.8). Each category is coloured or shaded differently so that it can be distinguished clearly from the other categories. Pie charts should only be used when there are few categories.

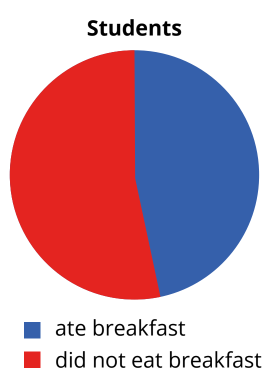


FIGURE 1.4.8 This pie chart presents data on the breakfast habits of students.

A circle is equal to 360°. To draw a pie chart, you must find how many degrees are needed for each category. This can be done as follows.

- Add the amounts in each category to find the total.
- Divide 360° by the total (this will tell you how many degrees of the circle one value is worth).
- Multiply the answer by the amount in the first category. Your answer will be in degrees, which can then be marked for the first category using a protractor on the circle.
- Repeat for each category.

Missing data

When you have missing data, leave a gap for it, as shown in Figure 1.4.9. Ensure that the axes are complete (do not skip values) and do not join the data points that have missing data points between them.

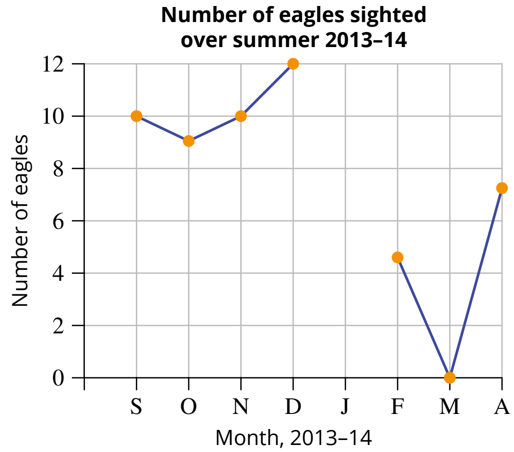


FIGURE 1.4.9 This line graph is missing the data from January.

Outliers

Sometimes when you collect data, there may be one point that does not fit the trend and is clearly an error. This is called an outlier. An outlier is often caused by a mistake made in measuring or recording data, or from a random error in the measuring equipment. If you have an outlier, you should include it in your graph, but ignore it when drawing the line of best fit (Figure 1.4.10).

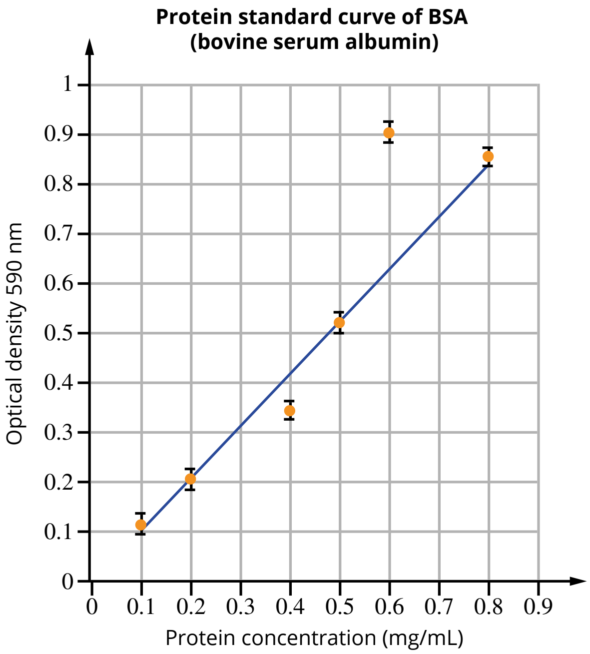


FIGURE 1.4.10 This line graph shows two outliers, which have been ignored when adding the line of best fit.

Distorting the truth

Poorly constructed graphs can distort the truth. For example, in Figure 1.4.11, you can see two graphs that show the same data—the test results of two groups of students. One group of students did not eat breakfast before doing the test and scored an average of 42 marks out of 50. The other group of students did eat breakfast and scored an average of 48 marks out of 50. One graph distorts the difference in marks between the two groups by using a scale of only 40 to 50 marks on the *y*-axis. It is important to make sure the graphs you create do not distort your data in this way. You should also be wary of distorted data when interpreting graphs in other publications.

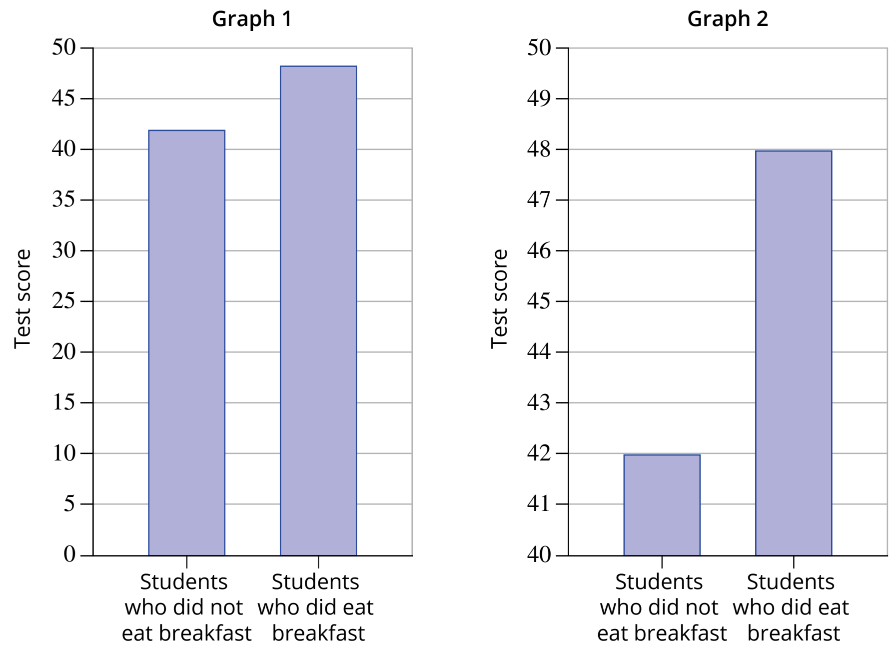


FIGURE 1.4.11 Graph 1 shows the difference in test scores between two groups of students out of the total 50 marks on the *y*-axis. Graph 2 shows the same difference, but within only a narrow range of marks on the *y*-axis, which distorts the difference between the groups, making it appear larger than it really is.

Relationships between variables

In experiments with continuous variables, such as a range of concentrations, temperatures or pH, different types of relationships may occur between variables. These relationships may be:

- **linear relationships**—variables that change in linear or direct proportion to each other produce a straight trend line (Figure 1.4.12a)
- **exponential relationships**—variables that change exponentially in proportion to each other produce a curved trend line (Figure 1.4.12b, c)
- **inverse relationships**—when one variable increases as the other variable decreases; this relationship may be linear or exponential (Figure 1.4.12d, e)
- no relationship—one variable will not change even if the other does (Figure 1.4.12f).

More complex relationships might have to be evaluated mathematically to obtain a formula that describes the trend line.

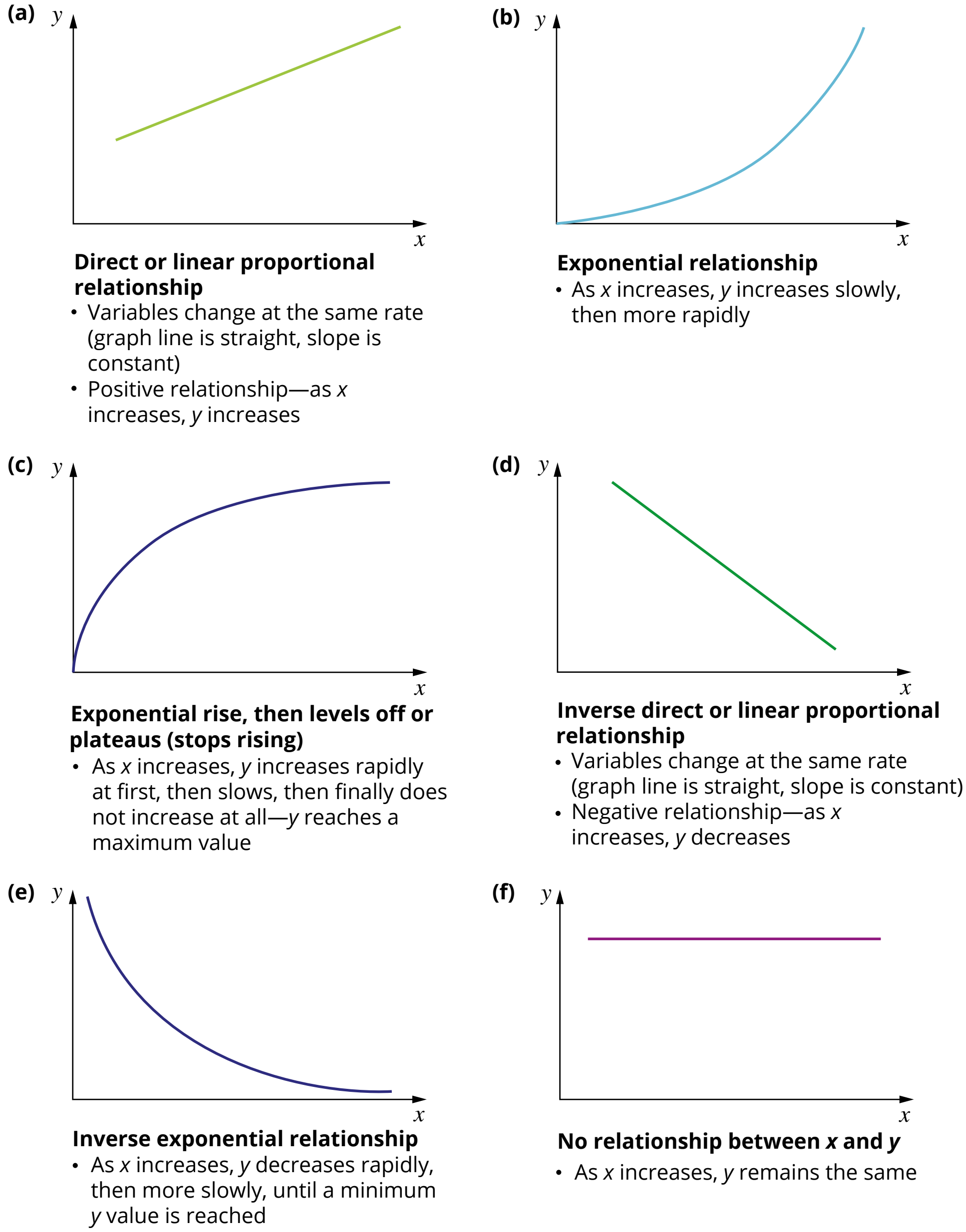


FIGURE 1.4.12 These line graphs illustrate common relationships between variables: (a) direct linear relationship, (b, c) exponential relationships, (d, e) inverse relationships, (f) no relationship.

1.4 Review

SUMMARY

- Descriptive statistics can be used for qualitative and quantitative data.
- Descriptive statistics include three measures of central tendency: mean, median and mode.
- To present data properly, the mean and its uncertainty should be included. Other statistical measures, such as mode and median, may also be useful for analysing and presenting data.
- Tables are used to record raw and processed data.
- Tables allow the presentation of more detail, while graphs allow trends to be shown more clearly.
- When presenting the results of an investigation, do not distort the truth—this includes selecting appropriate scales on graph axes, including outliers in graphs and including and explaining all errors.

KEY QUESTIONS

1 What is the difference between quantitative and qualitative data?

2 Identify which of the following pieces of information about plant material used in a plant hormone experiment are qualitative and which are quantitative. Place a tick in the appropriate column.

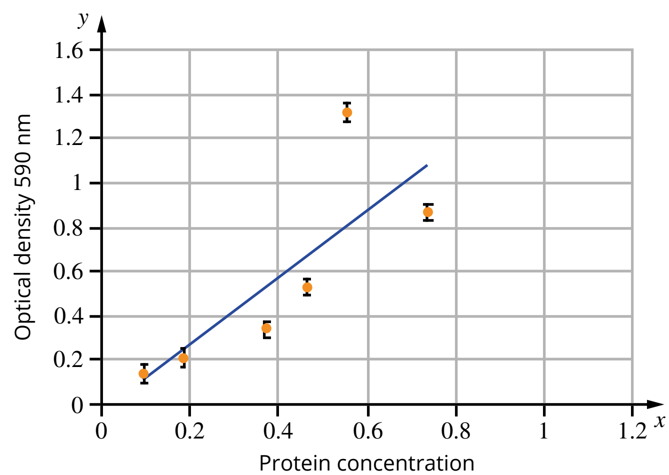
Information	Qualitative	Quantitative
leaf colour		
leaf smoothness		
length of stem		
number of leaves		
presence of roots		
change in internode length		

3 State the median, mode, mean and uncertainty of the following data: 21, 28, 19, 19, 25, 24, 20.

4 Using the student's results below, draw an appropriate graph.

	Mining temperatures			
Mine A				
Depth	Surface	300 m	700 m	1.0 km
Temperature	15°C	28°C	49°C	62°C
Mine B				
Depth	Surface	600 m	1.5 km	3.5 km
Temperature	20°C	25°C	37°C	55°C

5 Describe at least four ways the graph below could be improved.



6 Distinguish between the times when a line of best fit graph should be used and the times when a ruled graph line from point to point is more appropriate.

7 What are outliers, and what is the statistical measurement most affected by them?

8 **a** Give two reasons why is it important to accurately represent data from your own investigations.

b Explain why is it important to be able to interpret and understand representations of scientific data.

1.5 Analysing data and information

Now that you have thoroughly researched your chosen topic, conducted the investigation and collected the data, it is time to bring all this information together. You now need to analyse your results to better understand the biological processes behind them.

ANALYSING AND EVALUATING DATA

The results of an investigation need to be analysed, interpreted and evaluated. In a scientific report, this takes place in the discussion section.

The key sections of the discussion are:

- analysing and evaluating the data
- evaluating the investigative procedures
- explaining the link between the investigation's findings and the relevant biological concepts.

When you write the discussion, consider the message you want to convey to the audience. Statements need to be clear and concise. At the conclusion of the discussion, the audience must have a clear idea of the context, results and implications of the investigation.

When analysing your data, it is important to ask the following questions and include the answers in the discussion section of your report.

- Is there a pattern, trend or relationship between the independent and dependent variables? (See Section 1.4 for identifying trends in graphs).
- Describe what kind of pattern you found and specify under what conditions it was observed.
- Are there any errors, uncertainty or limitations in the data you have collected?
- If so, these should be acknowledged and explained. Perhaps a larger sample or further variations in the independent variable would lead to a stronger conclusion.
- Have other researchers found similar or different results?
- Discuss why the results of other investigations might be similar or different.
- What is the relevance of your investigation?
- Discuss why your investigation is important and the value that it has for society, the environment, your local community or the advancement of scientific knowledge.
- What are the future directions of this research?
- Include suggestions for ways you could improve future investigations.

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PRIMARY DATA QUALITY

The results of your data analysis will only be as good as the quality of the data. A well-designed scientific experiment should produce accurate, precise, reliable and valid results. You should consider all of these factors when collecting primary data in your practical investigations, and when you assess the quality of secondary data from other sources.

Accuracy and precision

In science and statistics, the terms 'accuracy' and 'precision' have very specific and different meanings.

- **Accuracy** is the ability to obtain the correct measurement. To obtain accurate results, you must minimise systematic errors.
- **Precision** is the ability to consistently obtain the same measurement. To obtain precise results, you must minimise random errors.

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Scientific data

All scientists strive to measure and report accurate and precise results. However, very precise measurements can be unwieldy—imagine entering a calculation with five numbers that were all measured to 20 decimal places! Scientists therefore restrict some measurements to a certain amount of significant figures or decimal places.

For example, some digital scales display mass as three significant figures (e.g. 1.01 g), while others display mass as six significant figures (e.g. 1.00001 g). The mass of the same object may be displayed as 3.46 g or 3.4578 g on different scales. Neither measurement is incorrect, but 3.4578 g is the more precise measurement.

Be aware that some scientific data can vary depending on the source. Always check that the data you are using has come from a reliable source.

To understand more clearly the difference between accuracy and precision, think about firing arrows at an archery target (Figure 1.5.1). Accuracy is being able to hit the bullseye, whereas precision is being able to hit the same spot every time you shoot. If you hit the bullseye every time you shoot, you are both accurate and precise (Figure 1.5.1a). If you hit the same area of the target every time, but not the bullseye, you are precise but not accurate (Figure 1.5.1b). If you hit the area around the bullseye each time, but don't always hit the bullseye, you are accurate but not precise (Figure 1.5.1c). If you hit a different part of the target every time you shoot, you are neither accurate nor precise (Figure 1.5.1d).

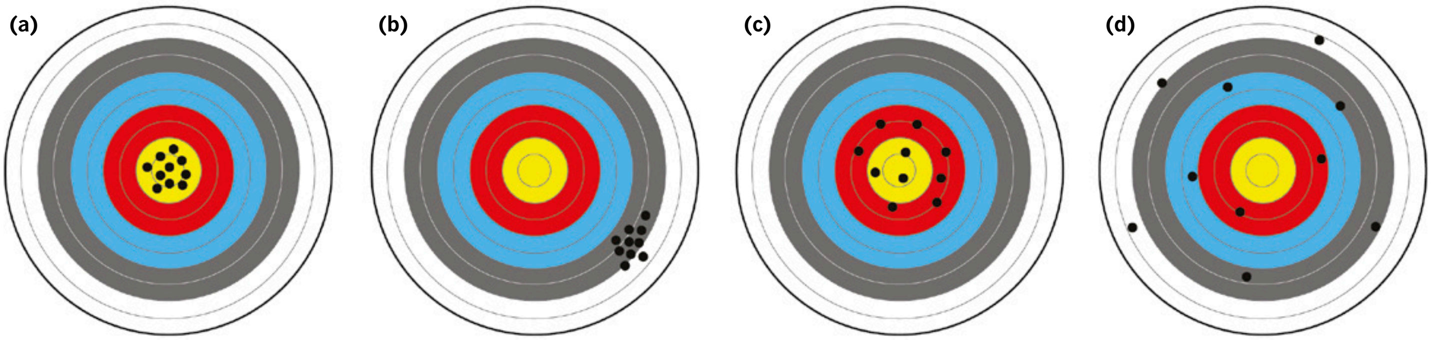


FIGURE 1.5.1 Examples of accuracy and precision: (a) both accurate and precise, (b) precise but not accurate, (c) accurate but not precise, and (d) neither accurate nor precise

Recording numerical data

When using measuring instruments, the number of **significant figures** (or digits) and decimal places you use is determined by how precise your measurements are.

This depends on the scale, accuracy and precision of the instrument and technique you are using (Figure 1.5.2). For example, a beaker is used to measure volumes approximately and has limited accuracy, e.g. ±5%. A graduated pipette is more accurate, with accuracies of ±0.1% or ±0.2%. Your pipette may be accurate, but if your technique using the pipette is variable, the overall accuracy and precision will be limited.

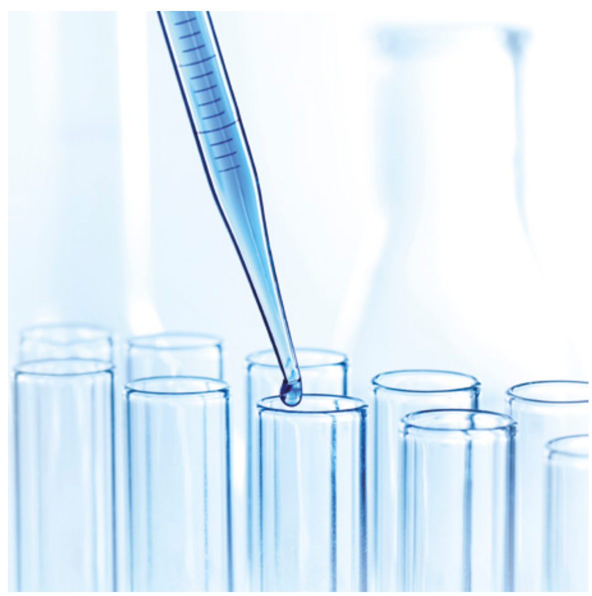


FIGURE 1.5.2 A 5 mL graduated pipette can measure volumes to an accuracy of one-hundredth of a millilitre, or 5 mL ± 0.01 mL. The pipette has major divisions of 1 mL and minor divisions of 0.1 mL. You can estimate to 0.01 mL and record volumes to two decimal places: for example, 3.80 mL or 4.52 mL.

When you record raw data and report processed data, use the number of significant figures available from your equipment or observation. Using either a greater or smaller number of significant figures can be misleading. For example, Table 1.5.1 shows measurements of five tissue samples taken using an electronic balance accurate to two decimal places. The data was entered into a spreadsheet to calculate the mean, which was displayed with four decimal places. You would record the mean as 20.83 g, not 20.8260 g, because two decimal places is the precision limit of the instrument. Recording 20.8260 g would be an example of false precision.

TABLE 1.5.1 An example of false precision in a data calculation

Sample	1	2	3	4	5	Mean
Mass (g)	20.13	20.62	21.22	20.99	21.17	20.8260

USING AND EVALUATING SECONDARY DATA

To use secondary data, you must first decide whether it is good enough to rely on. The best secondary data is found in peer-reviewed scientific journals (including online journals) and books. However, this information can become outdated quickly as scientific knowledge is advanced by new research. As a rule of thumb, it is not advisable to rely on information from publications more than 10 years old.

You can use secondary data from other sources too, but this data is usually less reliable than peer-reviewed sources. Whatever sources you use, you still need to check that the data is precise, accurate, reliable and valid. You also need to acknowledge these sources by citing them in the text, and referencing them accurately in your reference list.

Evaluating accuracy

To evaluate the accuracy of secondary data, check the procedures (also called the methods) to see whether steps were taken to identify random errors. If the data has been analysed, check that the type of analysis was appropriate.

Evaluating reliability

To evaluate the reliability of secondary data, check whether the experimental procedures were conducted in a scientifically reliable way.

- Are the materials and procedures clearly stated?
- Were enough replicates used?
- Was the population size large enough?
- The results should be repeatable, and ideally will have already been reproduced by other researchers. When reviewing the scientific literature, it is important to review several articles to see if the results support or contradict each other.

Peer-reviewed means that other scientists have checked the information and have agreed that it is appropriate for publication.

Evaluating validity

To evaluate the validity of secondary data, check whether the research tested the stated hypothesis and covered the stated purpose (or aims). An investigation should obtain data that is relevant to the hypothesis. If it does not, then the study is invalid. You should also check whether there was appropriate randomisation and that one or more controls were included.

Evaluating websites

Remember that anyone can publish anything on the internet, so it is important to evaluate the credibility, currency and content of online information.

- Credibility—consider who the author is, their qualifications and expertise; check for their contact information and for a trusted abbreviation in the web address, such as .gov or .edu (websites using .com may have a bias towards selling a product, and .org sites might have a bias towards one point of view).

- Currency—check the date the information you are using was last revised.
- Content—consider whether the information presented is fact or opinion; check for properly referenced sources; compare to other reputable sources, including books and science journals.

Evaluating books and journals

Your textbook should be your first source of reliable information. Other information should agree with this. Articles published in journals can often present findings of new research, which may or may not be confirmed later, so be careful not to treat such sources of information as established fact. Because scientific journals are peer-reviewed, they have more credibility than other sources such as newspaper articles or general websites.

Summary of evaluating primary and secondary data

Table 1.5.2 summarises some factors to consider when evaluating and using secondary data. Make sure you consider all the factors that might affect the quality of the data when you are deciding whether to use it in your research.

TABLE 1.5.2 Summary of factors affecting the quality of primary and secondary data

	Primary data	Secondary data
Accuracy	• use appropriate and calibrated instruments • address systematic errors	• use reputable sources, such as peer-reviewed journals and books • check that systematic errors were addressed
Precision	• use an appropriate number of significant figures • address random errors	• check that random errors were addressed • check that any data analysis was appropriate
Reliability	• perform repeat readings • if possible, repeat your experiment	• check that the experimental procedures were stated and are repeatable, and that replicates and appropriate sample sizes were used • check that information is consistent with other reputable sources
Validity	• ensure your experiment tests your hypothesis • randomise your sample and use one or more controls	• check that the results relate to the hypothesis and purpose • check that samples have been randomised, and one or more controls have been used

WS 1.2

1.5 Review

SUMMARY

- The key steps when analysing and discussing data are:
  - analysing and evaluating the data
  - evaluating the investigative procedures
  - explaining the link between the investigation findings and the relevant biological concepts.
- Accuracy is the ability to obtain a correct measurement.
- Precision is the ability to consistently obtain the same measurement.
- Reliability is the ability to reproduce your results.
- Validity refers to whether your results are real results and whether they apply to all situations.
- Before using secondary data, such as books, journals and websites, you must evaluate whether it is accurate, reliable, valid and up to date.

KEY QUESTIONS

1 Identify the type of error associated with:
   a inaccurate measurements
   b imprecise measurements.

2 Describe the difference between replication and repeat trials.

3 A scientist carries out a set of experiments, analyses the results and publishes them in a scientific journal. Other scientists in different laboratories repeat the experiment, but do not get the same results as the original scientist. Suggest several possible reasons that could explain this.

4 A student conducted an experiment on *Chlorella*, a genus of unicellular freshwater algae (see the experimental procedure to the right). Due to equipment limitations (only two oxygen sensors were available), only two sets of data could be collected at one time.
   a Suggest a hypothesis for this experiment.
   b Identify the independent variable.
   c Identify the dependent variable.
   d Identify the controlled variables.
   e Will the results be objective or subjective? Explain.
   f Suggest ways to increase the reliability and validity of this experiment.
   g What conclusion would you draw from this experiment?
   h Will the conclusion be valid for all algae? Explain.

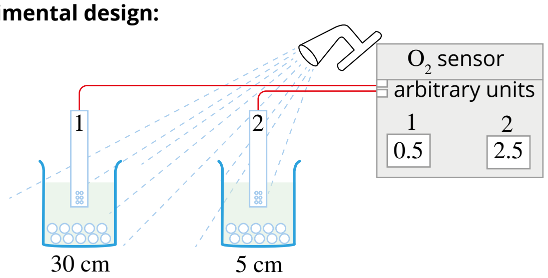
Purpose: To investigate the effect of light intensity on photosynthesis in *Chlorella*.

Hypothesis:

Materials:
- freshly prepared alginate balls with *Chlorella* (unicellular alga)
- two equal-sized tubes
- two dissolved oxygen sensors and data logger
- bright fibre optic light

Procedure:
1. Add 10 mL tap water to each tube.
2. Add 10 algae balls to each tube.
3. Place a probe for detecting dissolved oxygen into each tube and connect to the data logger.
4. Place tube one 30 cm from the light source. Place tube two 5 cm from the light source.
5. Turn on the light and measure the oxygen concentration over 24 h.

Experimental design:



1.6 Problem solving

In this section, you will learn about using scientific evidence from your investigation, and how to use critical thinking skills to improve your understanding of the scientific concepts underlying your investigation. You will also learn how modelling is a useful way to explain biological concepts, make predictions and solve problems.

DISCUSSING RELEVANT BIOLOGICAL CONCEPTS

To make an investigation more meaningful, it should be explained within the right context—that is, related biological ideas, concepts, theories and models. Within this context, you can explain the basis for the hypothesis. For example, if you were studying the impact of plant biomass on the level of dissolved carbon dioxide in pond water, you could include the information in Table 1.6.1 in your discussion.

TABLE 1.6.1 Examples of how to include biological concepts in your discussion

Key ideas	Example
definitions of key terms	'plant biomass', 'dissolved carbon dioxide' and 'pond water'
relationship between variables	Plant biomass is the independent (experimental) variable. Dissolved carbon dioxide in pond water is the dependent (measured variable). Temperature is a controlled variable.
hypothesis	If plant biomass reduces dissolved carbon dioxide levels in water and plant biomass in a pond is increased, then the dissolved carbon dioxide levels in the pond water will decrease.
biological principles	The decrease in dissolved carbon dioxide is due to an increase in the rate of photosynthesis when plant biomass is increased. Photosynthesis uses carbon dioxide, and therefore reduces the levels of dissolved carbon dioxide in water and carbon dioxide in the atmosphere.
sources of error	Reduce random error by repeating measurements and calculating average; ensure the same equipment and procedures are used in repeat trials; ensure controlled variables remain constant.

Relating your findings to a biological concept

During the data processing and analysing stage of your investigation (Sections 1.4 and 1.5), you identified trends or patterns in your data. This is the framework in which you should discuss whether the data supported or refuted the hypothesis. Ask questions such as the following:

- Was the hypothesis supported?
- Has the hypothesis been addressed with the data obtained? (If not, give an explanation of why this is so and suggest what could be done to either improve or complement the investigation.)
- Do the results contradict the hypothesis? If so, why? (The explanation must be plausible and based on the results and previous evidence.)

Providing a theoretical context also allows you to compare your results with existing relevant research and knowledge. After identifying the major findings of the investigation, you can ask some of the following questions:

- How does the data fit with the literature?
- Does the data contradict the literature?
- Do the findings fill a gap in the literature?
- Do the findings lead to further questions?
- Can the findings be extended to another situation?

Be sure to discuss the broader implications of your findings. Implications are the bigger picture; outlining them for the audience is an important part of the investigation. Ask questions such as the following:

- Do the findings contribute to or affect the existing literature and knowledge of the topic?
- Are there any practical applications for the findings?

DRAWING EVIDENCE-BASED CONCLUSIONS

A conclusion is usually a paragraph that links the collected evidence to the hypothesis. It provides a justified response to the inquiry question.

Indicate whether the hypothesis was supported or refuted, and the evidence on which this is based (that is, the results). Do not provide irrelevant information. Only refer to the specifics of the hypothesis and the inquiry question. Do not make generalisations.

Read the examples of strong and weak conclusions in Table 1.6.2 and Table 1.6.3 for the hypothesis and inquiry question shown.

TABLE 1.6.2 Examples of strong and weak conclusions to the hypothesis

Hypothesis: If plant biomass reduces dissolved carbon dioxide levels in water and plant biomass in a pond is increased, then the dissolved carbon dioxide levels in the pond water will decrease.

Weak conclusion	Strong conclusion
The dissolved carbon dioxide levels in the pond water decreased as plant biomass increased.	A 10 g increase in plant biomass resulted in a 7% decrease in dissolved carbon dioxide in the pond water.

TABLE 1.6.3 Examples of strong and weak conclusions in response to the inquiry question

Inquiry question: Does temperature affect the dissolved carbon dioxide levels in pond water?

Weak conclusion	Strong conclusion
The results show that temperature does affect the dissolved carbon dioxide levels of water.	Analysis of the results showed an inverse relationship between pond water temperature and carbon dioxide levels. When the temperature increased from 5°C to 40°C, carbon dioxide levels decreased by 24%. These results support the current knowledge that rising water temperatures reduce the ability of the water to dissolve carbon dioxide.

INTERPRETING SCIENTIFIC AND MEDIA TEXTS

Sometimes you may be required to investigate claims and conclusions made by other sources, such as scientific and media texts. As discussed in Section 1.5, some sources are more credible than others. Once you have analysed the validity of the primary or secondary text, you will be able to follow the same steps described above when you evaluate their conclusions.

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MODELS

Scientific **models** are used to create and test theories and explain concepts. Different types of models can be used to study systems, such as parts of the body or particular environments. However, each model is limited by the type of information it can provide.

Modelling concepts

Models are created to answer specific questions. How a model is designed will depend on the questions you want to answer. The two most familiar types of models are visual models and physical models, but mathematical models and computational models are also common. Models help to make sense of ideas by visualising:

- objects that are difficult to see because of their size (too big or too small) or position, such as an ecosystem, a cell or a heart
- processes that cannot easily be seen directly, such as digestion and feedback loops
- abstract ideas, such as energy transfer and the particulate nature of matter
- complex ideas, such as climate change.

For example, the greenhouse effect on Earth can be modelled using a real greenhouse (Figure 1.6.1).

FIGURE 1.6.1 The glass in this greenhouse behaves like greenhouse gases, such as carbon dioxide and methane, in Earth's atmosphere. Like greenhouse gases, the glass lets the sunlight in, but prevents the reflected heat from escaping back out into space.

Using digital modelling software to develop physical or mathematical models has improved our understanding in many areas. For example, flight simulators have enabled pilots to learn how to fly new aircraft, and dissection and surgery simulations can replace the practice of dissecting living organisms.

A deeper understanding of concepts can be developed through models. However, you should identify the benefits and limitations of a particular model before using it to represent a concept.

Visual models

Visual models are two-dimensional representations of concepts. Diagrams and flow charts are two examples. A picture of the human heart with red and blue colouring to represent oxygenated and deoxygenated blood is an example of a visual model (Figure 1.6.2). It is difficult for us to see this phenomenon, so models can be used to represent it. Computer technology, including two-dimensional and three-dimensional animations, has helped to create more detailed and realistic representations of biological processes.

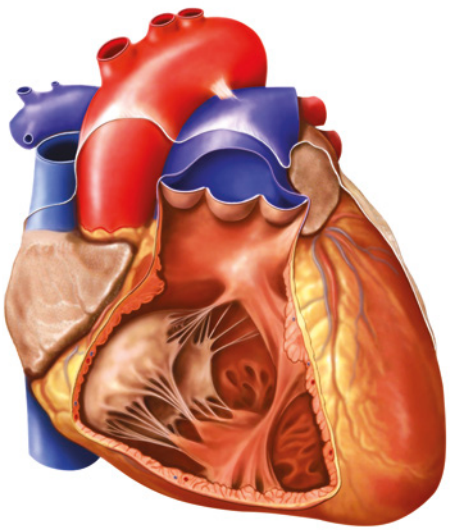


FIGURE 1.6.2 This visual model of the human heart shows the external structure and internal structure of the right ventricle.

Physical models

Physical models are three-dimensional versions of structures that can be scaled up or down. You have probably already used physical models, such as a human skeleton, many times in the classroom.

Although models help us to understand concepts, they are limited by how well they can represent what they are modelling. For example, although a plastic model of a lung does inflate and deflate, it does not take in oxygen and release carbon dioxide, and it is hard and solid, instead of soft and flexible.

When making physical models (Figure 1.6.3), it is important to consider what materials are used to represent the real structure, so that the model has fewer limitations. The materials you use to construct your model should relate to what you are modelling.

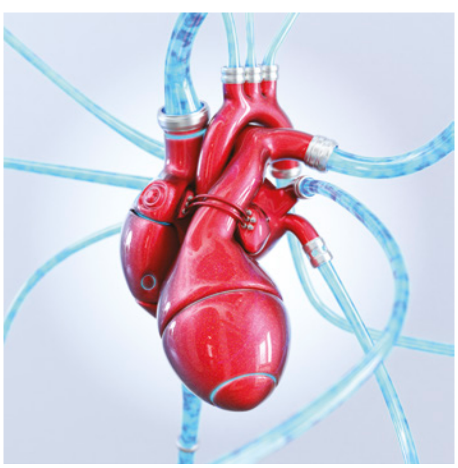


FIGURE 1.6.3 An artificial heart model made from metal (red) and plastic tubes (blue) is useful for showing the movement of blood into and out of the heart. However, it is not useful for showing the rhythmic contractions of the heart muscles, or for showing the internal structure of the heart.

Computer and mathematical models

Computer simulations and mathematical models can be used to model the complexity of whole cells, systems, organs or organisms. Such models can be used for testing hypotheses and conducting virtual experiments. Examples include:

- a virtual cell of the bacterium *Mycoplasma pneumonia*
- connections between cells (e.g. all of the neural connections in the brain are called the connectome)
- whole organs (e.g. virtual liver and heart)
- whole organisms (e.g. the nematode worm *Caenorhabditis elegans)*
- mathematical modelling showing how immune cells attack other cells
- gene interactions using data from the Human Genome Project
- relationships between genotypes and phenotypes, using gene and protein sequence databases
- protein structure and function, using protein sequence databases and three-dimensional molecular modelling.

Bionic models

Physical models are often used as a prototype for developing replacement limbs, such as prosthetic arms and legs. However, the complexity of biological systems limits the capacity of physical models, which usually focus on single functions, to replace non-functioning organs. By combining physical concepts with computer modelling of biochemical and physiological processes, researchers can develop models that mimic biological function.

For example, the pancreas is a complex organ with many different specialised cells and functions. Among these, endocrine cells detect blood glucose levels and release hormones to control blood glucose. Beta cells are a type of endocrine cell that can produce, store and release insulin; they are of interest when modelling diabetes. Researchers are developing a bionic pancreas to treat type 1 diabetes, which occurs when the beta cells are damaged. The bionic pancreas uses a glucose sensor to monitor blood glucose levels and a computer-controlled algorithm to determine the amount of insulin to be delivered by an insulin pump (Figure 1.6.4). Years of research and development are needed to gain enough understanding of the biological processes to develop such devices.

FIGURE 1.6.4 A bionic pancreas is a medical device developed for people with type 1 diabetes. The device monitors blood glucose concentration using a sensor and determines whether insulin is needed to maintain blood glucose in the normal range. A signal is then sent to the insulin pump, which releases glucagon.

Model organisms

Biologists use live bacteria, animals and plants as **model organisms** for the investigation of cells and systems **in situ** and **in vivo**. Most of the advances in our understanding of animal and plant biology, genetics, pathology and medicine have come from the use of model organisms. These include the bacterium *Escherichia coli*, the nematode *Caenorhabditis elegans* (Figure 1.6.5), rats, mice, the plant *Arabidopsis thaliana*, and the fruit fly *Drosophila melanogaster*. Animal model organisms are also useful for testing hypotheses that cannot be tested in humans for ethical reasons.

Studies that are in situ are 'in position' or 'in place', such as when studying cells functioning within an intact organ, or molecules in their normal cellular location.

Studies that are in vivo are 'within the living', such as when cells are studied in a living organism.

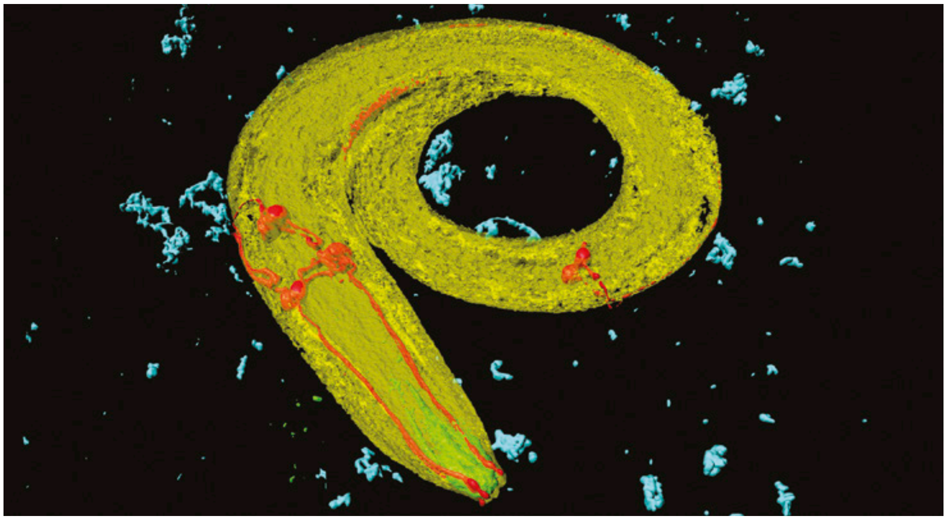


FIGURE 1.6.5 The nematode *Caenorhabditis elegans* is used as a model organism. It is a soil-dwelling worm about 1 mm long and is one of the most studied animals in biological and genetic research. We know a great deal about this organism, including its full genome, details of its life cycle, and the exact number of neurons in its nervous system (302) and how they form the nervous system. This confocal laser-scanning micrograph of *C. elegans* shows neurons stained green and the digestive tract stained red.

Studies that are **in vitro** are 'in glass' or in a dish or test tube, such as when cells are removed from the organism and studied in a culture dish (it doesn't have to be glass).

Studies that are in silico are 'in silicon', which refers to the silicon chips used in computers for computer simulations.

Efforts are being made to reduce the number of animals used in research, and strict ethical guidelines must be followed in their use. Studies performed in vitro, and advances in computer simulation, 'virtual' cells and organisms that have made in silico studies possible, reduce our reliance on live animals. However, keep in mind that the value and validity of a virtual model or simulation is only as good as the data and information used to construct the model. This information must ultimately come from living cells and organisms.

1.6 Review

SUMMARY

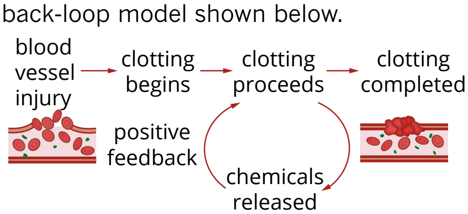
- To make an investigation more meaningful, it should be explained within the right context, referring to relevant biological ideas, concepts, theories and models.
- It is important to refer to credible sources of information when drawing evidence-based conclusions.
- Your conclusion should indicate whether the hypothesis was supported or refuted, and the evidence on which this is based.
- Models are useful tools that can be created and used to gain a deeper understanding of concepts.
- Models help to make sense of ideas by visualising microscopic objects, complex biological processes and abstract ideas.
- Some common types of models are visual, physical, mathematical and computational models.
- Visual models are two-dimensional representations of concepts, and include diagrams and flow charts.
- Physical models can be scaled-up or scaled-down three-dimensional versions of reality. The human skeleton is a physical model often seen in classrooms.
- Mathematical modelling and computer simulations can be used to test hypotheses and conduct virtual experiments. Computer simulations can be used to model the complexity of whole cells, systems, organs or organisms.
- Bionic models can be used to replace organs, such as a bionic pancreas.
- Biologists use model organisms, such as live bacteria, animals and plants, to investigate cells and systems.

KEY QUESTIONS

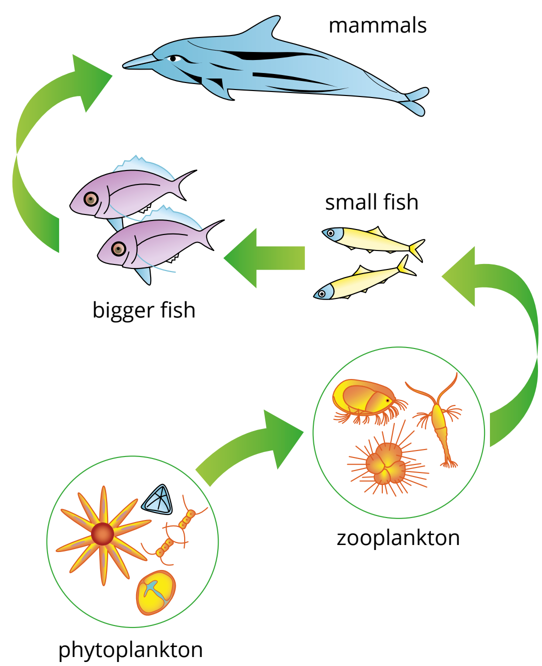
1 Which of the following would not support a strong conclusion to a report?
- **A** The concluding paragraphs are relevant and provide evidence.
- **B** The concluding paragraphs are written in emotive language.
- **C** The concluding paragraphs refer to the limitations of the research.
- **D** The concluding paragraphs suggest further avenues of research.

2 Identify the following conclusions as strong or weak:
- **a** The study found a significant ($P < 0.05$) positive correlation between habitat fragmentation and population extinction in the Riverine Plain grasslands in southern New South Wales.
- **b** The algae did not photosynthesise in the dark.
- **c** The results of the study proved that the hypothesis was true. No further research is required to ascertain the relationship between plant growth and soil nutrient availability.
- **d** In conclusion, the results show a significant ($P < 0.01$) negative relationship between water temperature and *Banksia marginata* seed germination time, rejecting the hypothesis and findings of similar research.

3 Discuss the benefits and limitations of using the feedback-loop model shown below.



4 Explain what is represented by the visual model below.



5 Explain the benefits of using a torso model to learn about the parts and relative positions of the organs in the human body.

6 Explain two limitations of using models.

7 Discuss how computer modelling could help in representing and learning scientific concepts.

1.7 Communicating

Now that you have thoroughly researched your topic, formulated an inquiry question and hypothesis, conducted experiments, and collected and analysed your data, it is time to present your findings. The final part of an investigation involves summarising the findings in an objective, clear and concise manner for your audience.

In this section, you will learn about different presentation formats, writing and presenting a well-structured scientific report, and evaluating and discussing the findings of your investigation in relation to your hypothesis and published research.

SELECTING THE PRESENTATION FORMAT

Although most presentations of research work will have the same elements, you can present information in many different ways. The format you choose will depend on the type of investigation, what stage the research is at, and the audience you are presenting to. Table 1.7.1 provides some options and hints for different formats.

TABLE 1.7.1 Common presentation formats, their characteristics and things you should remember when presenting your work

Format	Characteristics	Things you should include or remember
poster presentation	• visual display of information • suitable for presenting information to many people • summary of ideas	• a title that attracts attention • large headings that stand out • subheadings of a smaller size • attractive presentation • balance of written and visual material, such as diagrams, sketches, photographs, tables or graphs • writing large enough to read from a distance
scientific report	• presents clear and detailed information on a topic • suitable for providing detailed information to individuals	• include an introduction and sections covering materials and procedures, results, discussion and conclusions • use subheadings • mainly text, but can include diagrams, sketches, photographs, tables or graphs
oral communication with supporting slides or handouts e.g. digital presentation	• easy-to-follow format • good for presenting to a large audience • best if combined with a digital presentation (e.g. slideshow) • slides or handouts can summarise information covered in an oral presentation • handouts can be printed as a set of notes to be given to the audience	• use palm cards to glance at if needed • rehearse the presentation so you do not have to read the slides or palm cards word for word • maintain eye contact with the audience • speak clearly and at a volume that can be heard • don't fidget or wriggle around • stand up straight and look confident • stand to one side of the screen, not in front of it • slideshows are mostly visual with small amount of text • use the same background, format and colours throughout the slides • not too much text on each slide
online presentation e.g. website, blog	• can present visual and written information • accessible to a worldwide audience • easy to follow • easy to update with new information	• include hyperlinks to related information • include multimedia, such as video clips and audio, if appropriate • use the same background, format and colours throughout • use headings that stand out • list all the hyperlinked contents on the main page • include your name and credentials, and the date of publication

EFFECTIVE SCIENCE WRITING

Effective science writing is objective, clear and concise. It has a consistent narrative, and is backed up by visual support such as graphs and figures.

Planning is an important part of the writing process, and will help you present your ideas in a logical order. Write down all the main headings, and organise all the relevant information under each one, perhaps as dot points. This planning will help you to focus on writing your findings in the correct tone and style.

If you have time, it is a good idea to put your finished writing aside for a few days and then go back and read it over again, fixing anything that is incorrect or poorly written. Checking the spelling is also an essential part of editing your writing. Make sure the spellchecker is set to Australian English; the default setting is usually American English. But do not rely only on computer programs to check your spelling; they can make mistakes too, and often do not recognise scientific words.

Objective writing

Scientific reports should be written in an objective (unbiased) style. This is in contrast to literary writing, which often uses subjective (biased) techniques of persuasion (Table 1.7.2).

TABLE 1.7.2 Examples of unscientific and scientific writing

Unscientific writing examples	Scientific writing examples
Examples of biased and subjective language: • The results were weird/bad/atrocious/wonderful... • This produced a disgusting odour... • This is a major health crisis... • This breathtakingly beautiful golden bowerbird...	Examples of unbiased and objective language: • The results showed... • This produced a pungent odour... • This is a serious health issue... • The golden bowerbird...
Examples of exaggeration: • The object weighed a colossal amount... • No one has ever seen this phenomenon... • The magnesium exploded into flames... • Millions of ants swarmed over the nest...	Examples of accurate language: • The object weighed about 250 kg... • This phenomenon has not been reported previously... • The magnesium burned vigorously... • Ants swarmed over the nest...
Examples of everyday language: • The bacteria passed away... • The results don't... • We had a sneaking suspicion... • Previous researchers were slack and missed...	Examples of formal language: • The bacteria died... • The results do not... • We predicted/hypothesised/theorised... • Previous researchers did not notice that...

Qualified writing

It is best to avoid words that are absolute, such as always, never, shall, will or proven. Instead, qualify your writing using words such as may, might, possible, probably, likely, suggests, indicates, appears, tends, can and could.

Concise writing

To be concise, use short sentences with a simple structure. The opposite of concise writing is verbose (wordy) writing. When writing, think about how you could say the same thing using fewer words (Table 1.7.3). To help you see if your writing is verbose, try reading it out aloud. You will easily hear awkward sentence construction that is easy to skip over when reading silently to yourself.

TABLE 1.7.3 Examples of verbose writing and concise alternatives

Verbose	Concise
due to the fact that	because
Carlos undertook an investigation into…	Carlos investigated…
It is possible that the cause could be…	The cause may be…
a total of five experiments	five experiments
end result	result
in the event that	if
at the time of writing	currently
is well known to be	is
on an annual basis	yearly
until such time as	until
in the vicinity of	near
while in the process of preparation	while preparing
I am of the opinion that	I think

Voice

Voice means whether the subject of the sentence is the 'doer' or 'receiver' of the action. In the active voice, the subject is the doer; for example, 'We added 20 mL of sodium chloride to the beaker.' In the passive voice, the subject is the receiver; for example, '20 mL of water was added to the solution.' Choose the voice that helps you communicate your ideas clearly. This will usually be the active voice rather than the passive voice. Using the passive voice all the time can result in awkward and sometimes confusing sentences (Table 1.7.4). A mixture of active and passive voice is usually best.

TABLE 1.7.4 Examples of passive and active voice

Passive voice	Active voice
The temperature was controlled by a thermostat.	A thermostat controlled the temperature.
Fifty grams of marble chips were placed in a conical flask, then 10 mL of 2 M hydrochloric acid was slowly added.	We placed 50 g of marble chips in a conical flask and then slowly added 10 mL of 2 M hydrochloric acid.
The tree hollows were checked every morning by the observers.	The observers checked the tree hollows every morning.
The owls were seen using night-vision goggles.	We used night-vision goggles to see the owls.

Tense

Use the past tense when describing your research, including the planning, the experiment and the results, as well as the work of previous researchers. For everything else (including describing facts and theories) you should use the present tense. Avoid using the conditional tense (could or would) and the future tense (unless you are talking about something that has not yet happened).

Table 1.7.5 shows some examples of the correct and incorrect use of tenses in scientific writing.

TABLE 1.7.5 Examples of incorrect and correct use of tense

Incorrect tense	Correct tense
Zhu (2013) describes a similar phenomenon.	Zhu (2013) described a similar phenomenon.
The fish are then fed for five days on protein A.	The fish were then fed for five days on protein A.
The results suggested that killer whales were not disoriented by low-frequency sonar emissions.	The results suggest that killer whales are not disoriented by low-frequency sonar emissions.
The crayfish will burrow deeper if the water level falls.	The crayfish burrow deeper if the water level falls.
This would suggest that parrots could transmit the virus directly to humans.	This suggests that parrots can transmit the virus directly to humans.

Visual support

Use graphs or diagrams to present complex concepts or information. This will reduce the number of words you need, and also communicate your research more effectively to your audience. All visual material should have informative captions to help the reader easily understand what the image represents.

WRITING A SCIENTIFIC REPORT

Whether the investigation is presented as a poster, written report or oral presentation, the same key elements are included in the same sequence, as summarised in Figure 1.7.1.

Title	• concise • use key terms
Introduction	• relevant background information on the topic • what is already known on the specific issue • the question being addressed • purpose and hypothesis
Materials and procedures	• list all materials • step-by-step experimental procedures • diagrams or flow charts (optional)
Results	• descriptive/observational text • data tables and/or graphs • images: photos and/or diagrams
Discussion	• analysis • summary diagrams/charts may be suitable • conclusion: do the results support the hypothesis?
References and acknowledgements	• list all references • acknowledge all who helped

FIGURE 1.7.1 Elements of a scientific report or presentation

Title

The title should give a clear idea of what the report is about, without being too long. It should include key terms that tell the reader what your study focuses on.

Introduction

The introduction sets the context of your report. It introduces the key terms, the specific question to be addressed, and states your hypothesis. The introduction should also

outline relevant biological ideas, concepts, theories and models, referencing current literature, and show how they relate to your specific inquiry question and hypothesis.

For example, consider a student investigating the cellular processes affected by gibberellic acid, a growth-promoting plant hormone. The research and introduction for this investigation might include the following points:

- the name and chemical nature of the hormone
- where the hormone is found (natural or synthetic)
- what is currently known about the actions of the hormone
- the specific question being addressed
- the hypothesis.

While researching this topic, the student found prior evidence that suggests this hormone increases the height of some dwarf plants, but the mechanism for this effect was not clear. There were some reports of increased cell division, while other studies reported a change in cell length. The student's hypothesis was: 'If the hormone gibberellic acid increases cell length in dwarf pea plants and some plants are exposed to the hormone and others are not, then plants exposed to the hormone will grow faster than the plants that are not.'

Materials and procedures

The materials and procedures section lists all the materials that were used in the investigation, and describes in detail all the steps that were undertaken. For a poster presentation, use stepwise lists, diagrams of specific procedures or flow charts of the overall experimental design. Use enough detail to allow someone else to replicate your experiments. Your procedures need to be in the correct sequence, and include how you observed, measured, recorded and analysed the results. This section should also identify the independent, dependent and controlled variables.

Figure 1.7.2 shows an example of the materials and procedures section for an experiment on plant hormone action as it might be presented in a written report. For a poster presentation, the procedures may be easier to follow in a stepwise list accompanied by large, clearly labelled diagrams. Alternatively, flow charts are a good way to clearly present the procedures of an investigation.

Materials

- 20 dwarf pea plant seeds
- 3 pots and potting mix
- plant hormone—gibberellic acid (GA) solutions, 0.01% and 0.1%, diluted from 1% stock solution in distilled water (dH_2O)
- small spray bottles
- scalpel blade and forceps
- toluidine blue stain (0.025%)
- 1 M HCl
- microscope slides and coverslips
- compound light microscope

Procedures

Example experiment 1: Plant growth and treatment with GA

Dwarf pea seeds were germinated and transferred into three pots with potting mix, five plants per pot. After one week, when the seedlings were approximately 20 mm tall, plants were sprayed with either dH_2O, 0.01% GA or 0.1% GA (Figure 1). Plant height was measured one and two weeks later.

The independent variable in this experiment was the GA concentration, and the dependent variable was plant height.

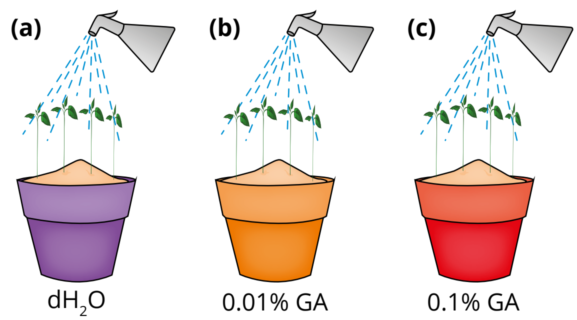


Figure 1: Seedlings were sprayed with dH_2O (a), 0.01% GA (b), or 0.1% GA (c).

FIGURE 1.7.2 Materials and procedures section from a report on a plant hormone action experiment

SKILLBUILDER L

Structuring body paragraphs

The body paragraphs of a report or essay need to be structured so that each idea is presented in a clear way. Good paragraphs build up to develop a report that has a logical flow.

One way to ensure each paragraph is structured well is to use the acronym TEEL.

Topic sentence

This establishes the key idea or argument that will be put forward in the paragraph. It supports the main proposition of the overall report.

Elaborate on the idea

Add further detail to the initial topic sentence.

Evidence

Provide evidence to support the idea or argument in the topic sentence.

Link back to the topic sentence

Summarise the argument in the paragraph and how it links to the overall proposition set out by the report.

Results

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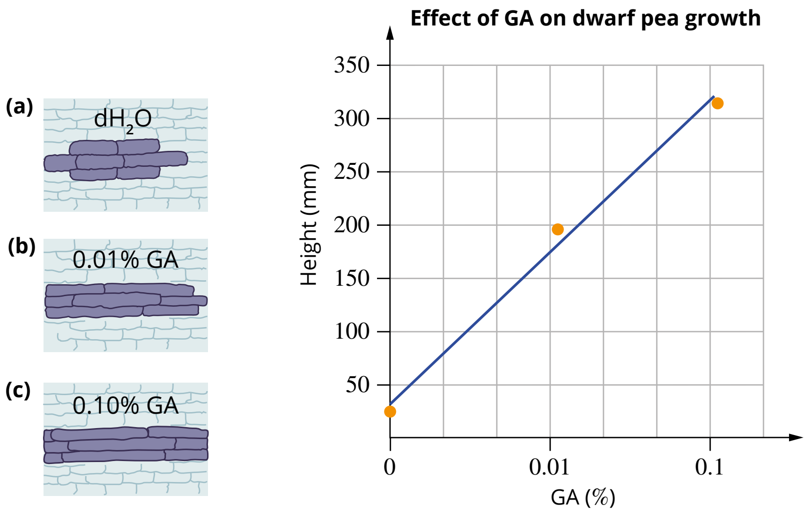
The results section is a record of your observations. It is where you present your data using graphs, diagrams, tables or photographs. In Section 1.4, you learnt how to use graphs and tables appropriately.

For the plant hormone experiment described above, the results section might include the following table and figures (Figure 1.7.3).



Plant no.	Plant height (mm) at different GA concentrations		
	0	0.01%	0.10%
1	23	117	158
2	20	210	378
3	22	240	320
4	30	211	377
5	31	198	363
mean	25	195	319

FIGURE 1.7.3 Example results section from a report on a plant hormone action experiment

Discussion

In the discussion you interpret the results and discuss how your findings relate to your initial question and hypothesis, the research of others, and the biological concepts outlined in the report's introduction.

Interpreting the results

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When you interpret your results, you need to state clearly whether a pattern, trend or relationship was observed between the independent and dependent variables. Describe what kind of pattern it was, and specify under what conditions it was observed. Section 1.4 covers the presentation and interpretation of results.

Evaluating the investigative procedures

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The discussion should evaluate your investigative procedures and identify any issues that could have affected data validity, reliability, accuracy or precision. This is covered in detail in Section 1.5.

Any possible sources of error in your experiment should be stated. Remember that controls are essential to the reliability and validity of your investigation. If you have overlooked or were unable to control a variable that should have been controlled, this may explain unexpected results.

Identify any ways your experiment could be improved. In the example plant hormone experiment, the experimenter should consider whether there were enough replicates to obtain reliable data, whether microscopy was a reliable way of determining cell number and cell length, whether the microscope was calibrated, and whether enough cells were viewed. When writing your report, provide specific suggestions for improvements to the procedures based on what you have learnt.

It is also important to acknowledge contradictions in data and information. Again, consider the example plant hormone experiment. Results from a second experiment (not shown here) showed a similar increase in cell length for both concentrations of GA, which is inconsistent with the effects of GA concentration

on plant height. This observation raises several questions. Is it a limitation of the experimental design or procedures? Are there more biological effects that are not detected or measured? In your discussion, acknowledge these sorts of issues and make suggestions for further experiments to address them.

Relating findings to biological concepts

In your introduction, you established a context. Now you have a framework in which to discuss whether your data supports or refutes your hypothesis. Providing context also enables you to compare your results with existing research and knowledge. Use the points in the Figure 1.7.4 to help frame your discussion.

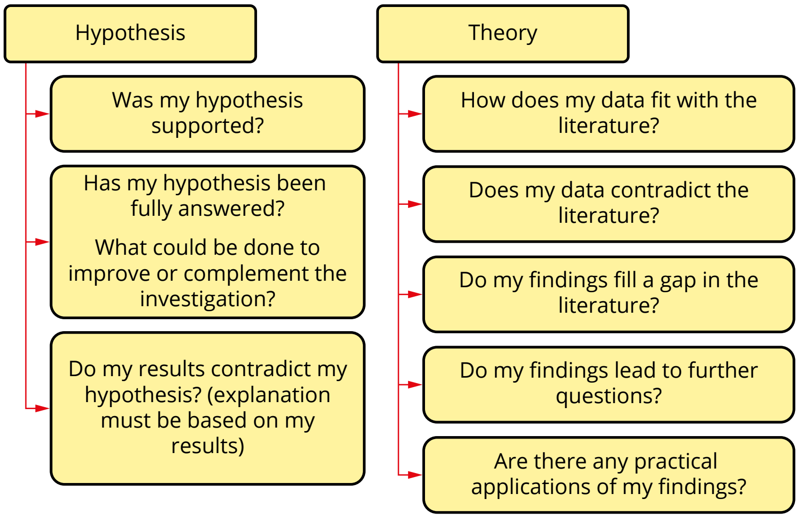


FIGURE 1.7.4 Points to help frame the discussion section of a scientific report

Conclusion

Your conclusion should be one or two paragraphs that link your evidence to your hypothesis. It should provide a carefully considered response to your inquiry question based on your results and discussion. You should clearly state whether your hypothesis was supported or not. Draw evidence-based conclusions by identifying trends, patterns and relationships in the data.

It is important to appreciate both your limitations and the limitations of the scientific method. Be careful not to overstate your conclusion. Your results will either support or not support the hypothesis. They will not 'prove' something is true, as you can only ever provide evidence that indicates the probability of something being true.

Do not provide irrelevant information or introduce new information in your conclusion. Refer to the specifics of your hypothesis and inquiry question, and do not make generalisations.

References

You must cite any information you have obtained from secondary sources in the text of your report, and provide a list of references at the end of your report. This demonstrates that you are aware of previous work in the area, and allows readers to locate sources of information if they want to study them further. The usual way of doing this is to give a short citation in the text, such as 'Meagher (2015)', and give the full reference in the reference list.

If you are stating factual information from another source, you can either quote it word for word, or rewrite it in your own words. However, if you rewrite it, you must make it clear that the information is not your own. **Plagiarism** (claiming that another person's work is your own) is not tolerated in scientific research.

Table 1.7.6 shows examples of ways to reference the three most common sources of information: journal articles, books and websites. Whichever style you use, make sure the references have a consistent format. For example, if you decide not to put parentheses around the date, make sure this style is used for every reference.

TABLE 1.7.6 Examples of citations and references for three common information sources

Source, information required for reference and example of citation in text	Example of the reference written out in the reference list
article in a scientific journal: • author, initials. (year). Title of article. *Journal title*, *volume number*(issue number), page numbers. • Meagher and Cairns (2014) discovered this genus recently in remote rainforest in tropical Queensland.	Meagher D. & Cairns A. (2014). *Entodontopsis* (Bryophyta: Stereophyllaceae) new to the Australian flora. *Telopea*, *17*, 295–301.
book: • author, initials. (year). *Title of book* (edition, if not first). City: Publisher. • Insects comprise more than 50% of the 1.4 million species described so far (Wilson 1992, page 126).	Wilson E.O. (1992). *The Diversity of Life*. Cambridge: Harvard University Press.
online article: • author, initials. (year). *Title of webpage or web document.* Retrieved day month, year, from URL. • Scientists believe they may have found a cure for white-nose syndrome that is wiping out bats in the United States (Lee 2015).	Lee J.J. (2015). *Killer fungus that's devastating bats may have met its match.* Retrieved 4 September, 2015, from http://news.nationalgeographic.com/2015/05/150527-bats-white-nose-syndrome-treatment-conservation-animals-science.

Acknowledgements

You need to acknowledge the work of anyone who has helped you in your research. This includes everyone from your fellow researchers, if you are working in a group, to people who helped you edit your report or artists who helped produce the images you used.

EDITING YOUR REPORT

Editing is an important part of the writing process. After editing your report, save new drafts with a different file name and always back up your files in another location.

Pretend you are reading your report for the first time when editing. Once you have completed a draft, it is a good idea to put it aside and return to it with 'fresh eyes' a day later. This will help you find areas that need further work and give you the opportunity to improve them. Look for content that is:

- ambiguous or unclear
- repetitive
- awkwardly phrased
- too lengthy
- not relevant to your inquiry question
- poorly structured
- lacking evidence
- lacking a reference (if it is another researcher's work).

Use a spellchecker tool to help you identify typographical errors, but first, check that your spellchecker is set to Australian English. Also be wary of words that are commonly misused, for example:

- where/were
- their/they're/there
- affect/effect
- which/that.

Check that you are using the correct units of measurement and scientific language.

1.7 Review

SUMMARY

- Your reports should include the following sections:
  - title
  - introduction
  - materials and procedures
  - results
  - discussion
  - conclusion
  - references
  - acknowledgements.
- The title should be short and give a clear idea of what the report is about, including key terms.
- The introduction should:
  - set the context of your report
  - introduce key terms
  - outline relevant biological ideas, concepts, theories and models, referencing current literature
  - state your inquiry question and hypothesis
  - relate ideas, concepts, theories and models to your inquiry question and hypothesis.
- The materials and procedures section should:
  - clearly state the materials required and the procedures used to conduct your study
  - be presented in a clear, logical order that accurately reflects how you conducted your study.
- The results section should state your results and display them using graphs, figures and tables, but not interpret them.
- The discussion should:
  - interpret data (identifying patterns, discrepancies and limitations)
  - evaluate the investigative procedures (identifying any issues that may have affected validity, reliability, accuracy or precision), and make recommendations for improvements
  - explain the link between investigation findings and relevant biological concepts (defining concepts and investigation variables, discussing the investigation results in relation to the hypothesis, linking the investigation's findings to existing knowledge and literature, and discussing the implications and possible applications of the investigation's findings).
- The conclusion should succinctly link the evidence collected to the hypothesis and inquiry question, indicating whether the hypothesis was supported or refuted.
- References and acknowledgements should be presented in an appropriate format.

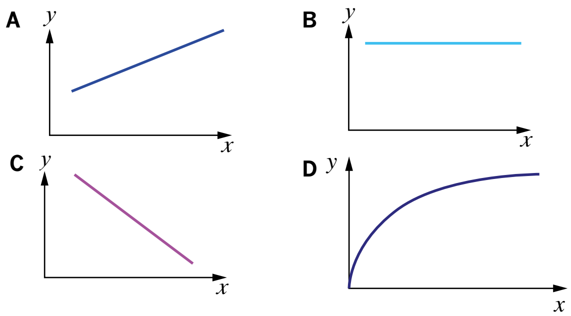
KEY QUESTIONS

1 List the elements of a scientific report.

2 What is the purpose of the discussion section of a scientific report?

3 **a** Which of the graphs below shows that the rate of transpiration increases as temperature increases?

b Which of the graphs below describes the following observation?
You are growing yeast in a low concentration of glucose, and observe that the yeast cells multiply exponentially, and then slow down. You interpret this to mean that the energy source has become depleted.



4 A scientist designed and conducted an experiment to test the following hypothesis: If eating fast food decreases liver function, then people who eat fast food more than three times per week will have lower liver function than people who do not eat fast food.

a The discussion section of the scientist's report included comments on the accuracy, precision, reliability and validity of the investigation. Read each of the following statements and determine whether they relate to precision, reliability or validity.

i Only teenage boys were tested.

ii Six boys were tested.

b The scientist then conducted the fast-food study with 50 people in the experimental group and 50 people in the control group. In the experimental group, all 50 people gained weight. The scientist concluded all the subjects gained weight as a result of the experiment. Is this conclusion valid? Explain why or why not.

c What recommendations would you make to the scientist to improve the investigation?

Chapter review

KEY TERMS

accuracy
aim
bar graph
calibrate
column graph
continuous variable
control group
controlled variable
data
database
dependent variable
descriptive statistic
discrete variable
error
ethics
experimental group
exponential relationship
falsifiable
hypothesis
in situ
in vitro
in vivo
independent variable
inference
inquiry question
inverse relationship
line graph
line of best fit
linear relationship
mark–recapture
mean
measurement bias
measure of central tendency
median
meniscus
mode
model
model organism
nominal variable
objective
observation
ordinal variable
outlier
peer-review
personal protective equipment (PPE)
pie chart
plagiarism
point sampling
polymerase chain
precision
primary data
primary investigation
primary source
principle
procedure
processed data
purpose
quadrat
qualitative data
qualitative variable
quantitative data
quantitative variable
random error
random selection
range
raw data
reaction (PCR)
reliability
repeat trial
replication
risk assessment
Safety Data Sheet (SDS)
sample size
scatterplot
scientific method
secondary data
secondary source
secondary-sourced investigation
selection bias
significant figure
subjective
systematic error
testable
theory
tissue culture
transect
trend line
uncertainty
validity
variable

REVIEW QUESTIONS

1 The following steps of the scientific method are out of order. Place a number (1–7) to the left of each point to indicate the correct sequence.

	Form a hypothesis
	Collect results
	Plan experiment and equipment
	Draw conclusions
	Question whether results support hypothesis
	State the biological question to be investigated
	Perform experiment

2 Scientists make observations and ask questions from which a testable hypothesis is formed.

a Define ‘hypothesis’.

b Three statements are given below. One is a theory, one is a hypothesis and one is an observation. Identify which is which.

i If ultraviolet (UV) rays cause damage to cells and skin is exposed to UV light, then skin cells will be damaged.

ii The skin burned when exposed to UV light.

iii Skin is formed from units called cells.

3 Write each of the three inferences below as an ‘if… then…’ hypothesis that could be tested in an experiment.

a Fungi produce compounds that kill bacteria.

b An enzyme in stomach fluid causes meat to be digested.

c Acidic conditions are not good for respiration in eukaryotic cells.

4 Which of these hypotheses is written in the correct manner? Explain why the other options are not good hypotheses.

A If light and temperature increase, the rate of photosynthesis increases.

B Respiration is affected by temperature.

C Light is related to the rate of photosynthesis.

D If motile algae are attracted to light and are presented with a light source, the algae will move toward the light.

5 **a** What do ‘objective’ and ‘subjective’ mean?

b Why must experiments be carried out objectively?

6 Write each of the five numbered inferences below as an ‘if … then …’ hypothesis that could be tested in an experiment.

a The grass receives the rain runoff from the path when it rains.

b The concrete path insulates the grass roots from the heat and cold.

c People do not walk on this part of the grass.

d The soil under the path remains moist while the other soil dries out.

e More earthworms live under the path than under the open grass.

7 Define ‘independent’, ‘controlled’ and ‘dependent’ variables.

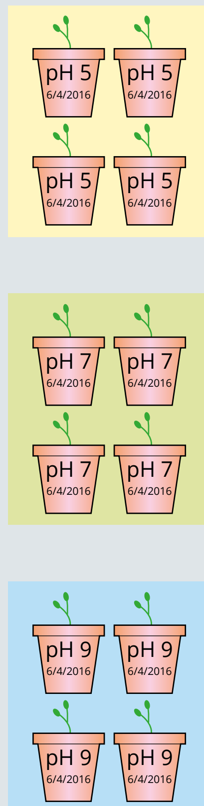
8 Design an experiment to test whether temperature is an important factor in the distribution of a mollusc species on a rocky coast. Clearly state the hypothesis that your experiment will test. Explain the procedures that you would use. Do not forget to include experimental controls.

9 Consider the seedling growth investigation below.

Purpose
To investigate the effect of pH on seedling growth.

Hypothesis
If there is a positive relationship between soil pH and seedling growth and the pH of the soil that seedlings are planted in is increased, then seedling growth will increase.

Procedure
1 Germinate 20 pea seeds on damp cotton wool and choose 12 seedlings with a height of about 12 mm.
2 Plant one seedling in each of 12 pots of the same size. For each pot, use 80 g of quality potting mix, and add 10 mL of tap water. Safety note: ensure that gloves and a mask are worn when handling potting mix, as it may contain harmful microbes.
3 Label each pot with the date and the pH treatment the soil will receive: four pots at pH 5, four pots at pH 7 and four pots at pH 9.
4 Weigh each pot to the nearest 0.1 g. Draw up a data table and record the results for each pot in a column with the heading 'Day 0'.
5 Reweigh the seedlings in their pots two days later. Record the results for each pot in the column for day 2.
6 Immediately after weighing, give each plant 10 mL of water at the appropriate pH according to the label on the pot.
7 Repeat steps 5 and 6 every two days for the next 10 days.
8 Keep plants in the same position where light is available to maintain light conditions.
9 Repeat steps 1–8 twice to reduce the chance of variability between trials.



a State the independent variable for the experiment.
b State the dependent variable for the experiment.
c List the controlled variables stated in the procedure.
d Explain the importance of controlling all variables except the dependent variable.

10 List three things that need to be considered when preparing a risk assessment.

11 List the components of the hierarchy of risk control in order from the least effective to the most effective.

12 Complete the following table to list and describe the three ways a laboratory chemical could enter the body, and how you might prevent this occurring.

Mode of entry	How the substance enters	Prevention

13 If you spilled a live bacterial culture on the lab bench, you would use paper towel to soak up the liquid.
a Who would you consult about proper clean-up procedures?
b What personal protective equipment (PPE) would you wear during this clean-up?
c What would you use to clean the bench top?

14 Suggest a procedure you could use for detecting photosynthesis in plants or algae.

15 You are learning about genetically inherited diseases and are searching for facts about cystic fibrosis. From the list below, which would be the best resource to use? Explain your answer.
A the book *Cystic Fibrosis*, published in 1997
B the article ‘Living with cystic fibrosis’ published in the *Daily Mail* on 23 February 2008
C the website www.cysticfibrosis.org.au, accessed on 30 October 2015

16 Identify which of the following pieces of information about a cup of coffee are qualitative, and which are quantitative. Place a tick in the appropriate column.

Information	Qualitative	Quantitative
cost $3.95		
robust aroma		
coffee temperature 82°C		
cup height 9 cm		
frothy appearance		
volume 180 mL		
strong taste		
white cup		

17 Using a Venn diagram, present the differences and similarities between discrete and continuous data.

18 Calculate the percentage change in mass for these plants exposed to light of different intensity.

Plant	Mass on Day 1 (g)	Mass on Day 2 (g)	% change
plant 1 (control)	13.4	13.7	
plant 2 (intense light)	14.8	15.3	
plant 3 (low light)	13.0	12.8	

19 Describe the advantages of calculating percentage change for the results of an experiment repeated by different groups of scientists.

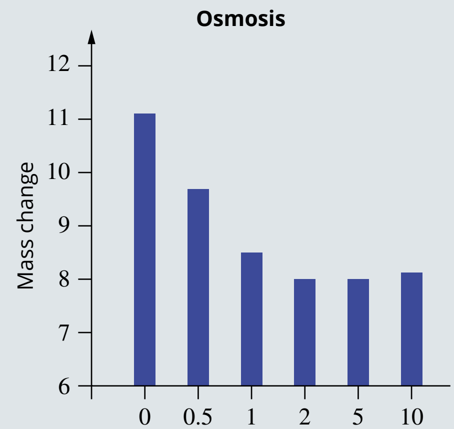
20 Immunologists have measured the levels of antibodies in blood serum to gather background data on population responses to infection. They collected the following data on the concentration of two different types of antibody, IgG and IgA, from subjects ranging in age from 6 months to 20 years (the antibody levels are listed in order of increasing age of subject).

- Age of subject: 6 months, 1, 2, 4, 10, 20 years
- Concentration of IgG (mg/100 mL): 300, 600, 800, 1000, 1500, 1500
- Concentration of IgA (mg/100 mL): 50, 100, 100, 150, 200, 400

a Prepare a data table.

b Prepare a graph of the data.

21 Describe at least four ways the graph below could be improved.



22 Explain why repeat trials and replication are necessary.

23 Consider the following experiment.

Hypothesis

If mineral water is better than tap water for the growth of plants, then seedlings watered with mineral water will grow more leaves than seedlings watered with tap water.

Experiment

Set up two identical trays of seedlings. They should have the same type of plant, age of plant, type of potting mix, drainage, and amount of sunlight and water. Everything should be the same except the type of water given to the plants.

Variables

Anything that could be different in the experiments must be kept the same. This includes everything listed above and even the height of the plants, the depth of potting mix and the intensity of the sunlight. These variables are kept the same—they are the controlled variables.

Only one variable is changed—the type of water. It is the effect of this variable that we are measuring. It is the independent variable. Its measurement should be objective (be able to be measured quantitatively).

The independent variable—the type of water—may change the number of leaves. The number of leaves is the dependent variable. The number of leaves depends on the type of water.

Results

Measure or count the number of leaves on each plant. This will give you objective results. Your friends could replicate the experiment at their houses. When you and your peers have repeated the experiment many times on different plants, the results can become a generalisation.

a In this experiment, what does the term 'sample size' refer to?

b Identify the controlled variables.

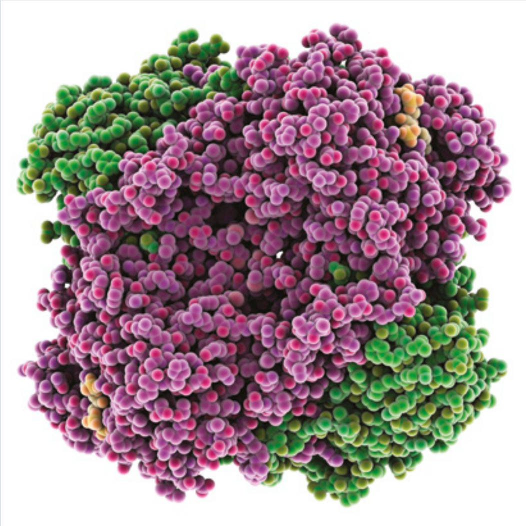
c Identify the independent and dependent variables.

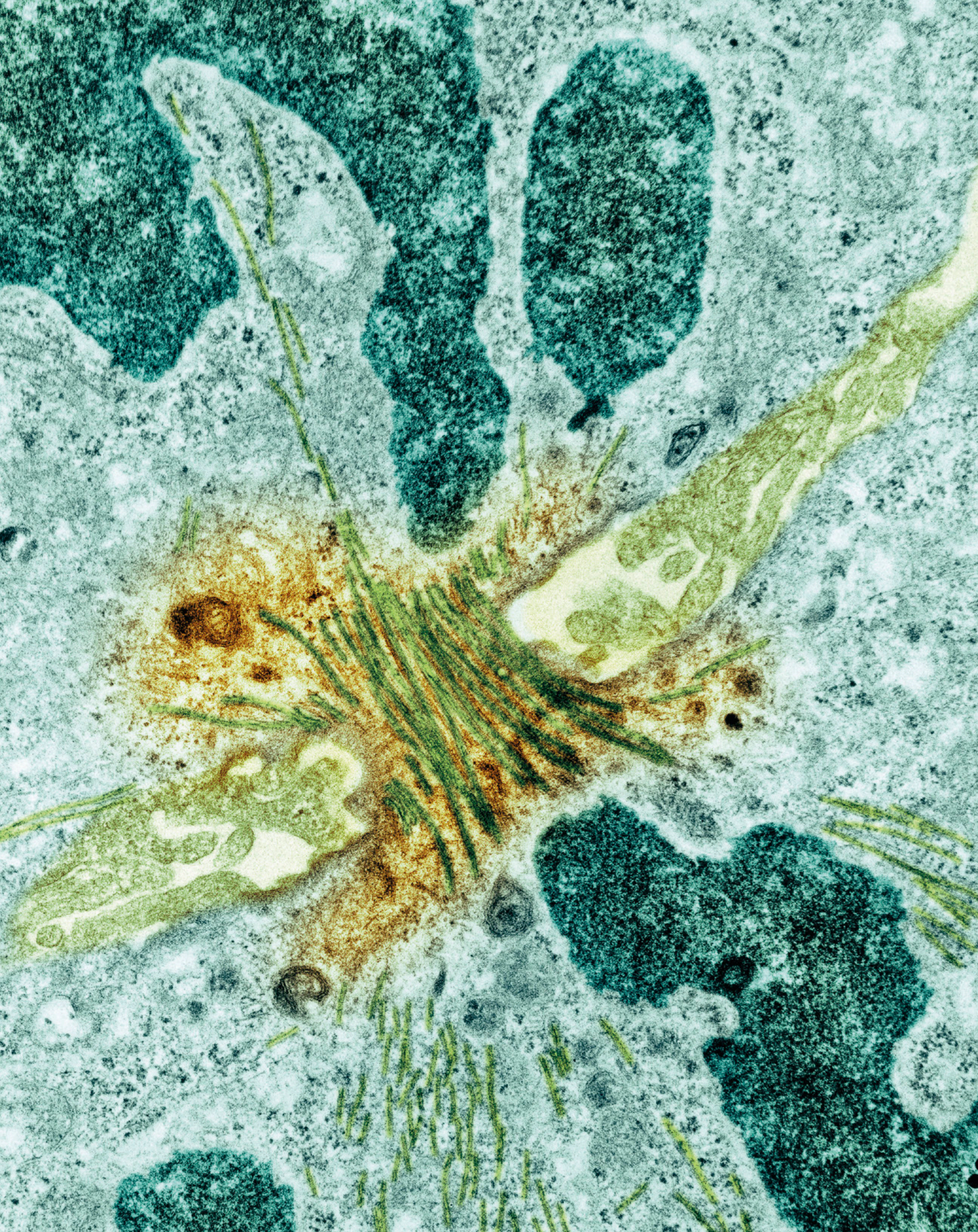
d Will the results be objective or subjective? Explain.

e Will the results be valid for all plants? Explain.

24 Explain what the visual model below represents. Why is this a useful model in science classrooms?

25 Below is a molecular model of the enzyme catalase, which converts hydrogen peroxide to water and oxygen. Suggest reasons why scientists construct molecular models in addition to simple diagrams or a written description of its molecular composition.





MODULE 1

Cells as the basis of life

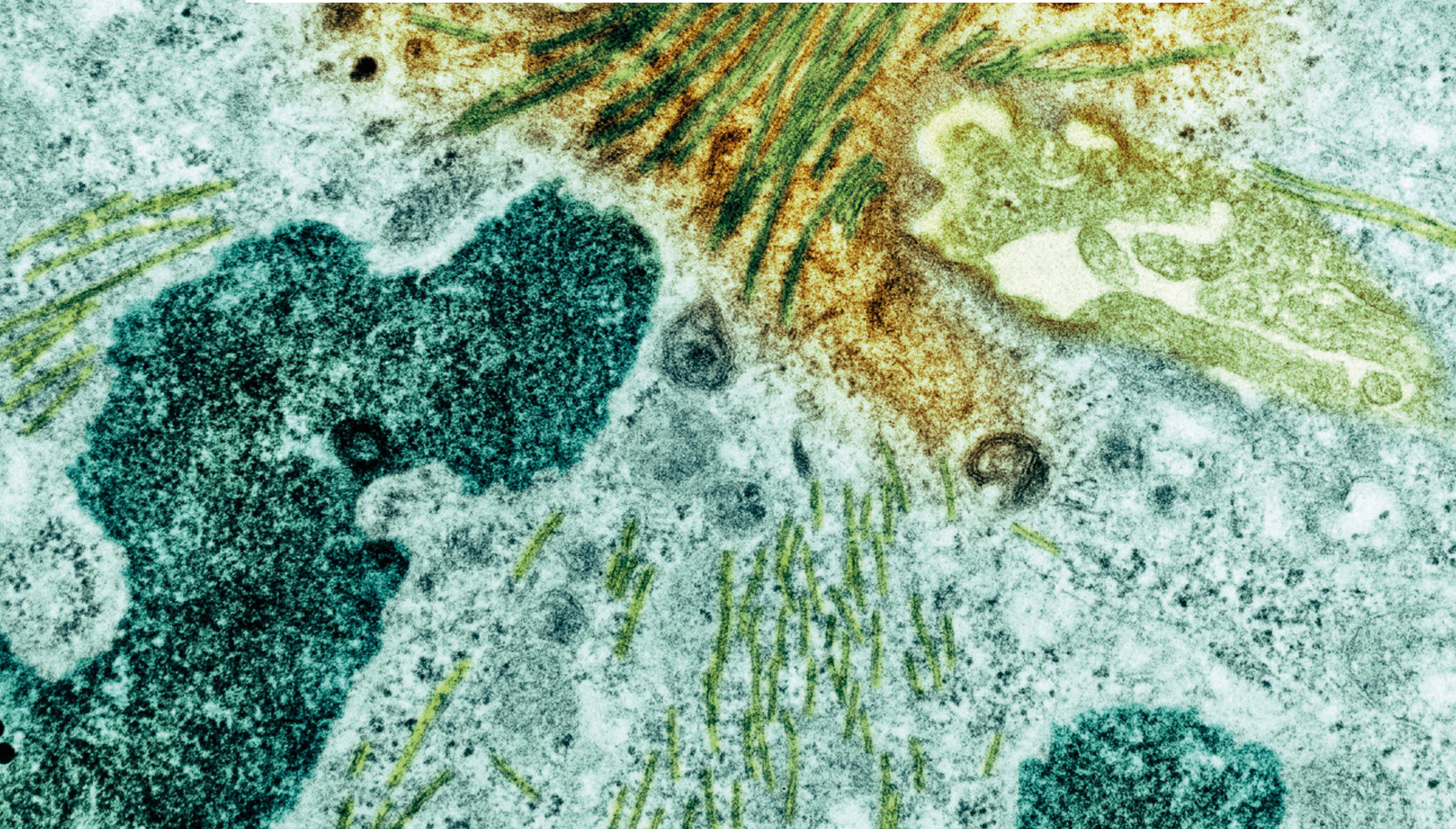
Cells are the basis of life. They coordinate activities to form colonial and multicellular organisms. This module examines the structure and function of organisms at both the cellular and tissue levels in order to describe how they facilitate the efficient provision and removal of materials to and from all cells in organisms. You will be introduced to and investigate biochemical processes through the application of the Working scientifically skills and processes.

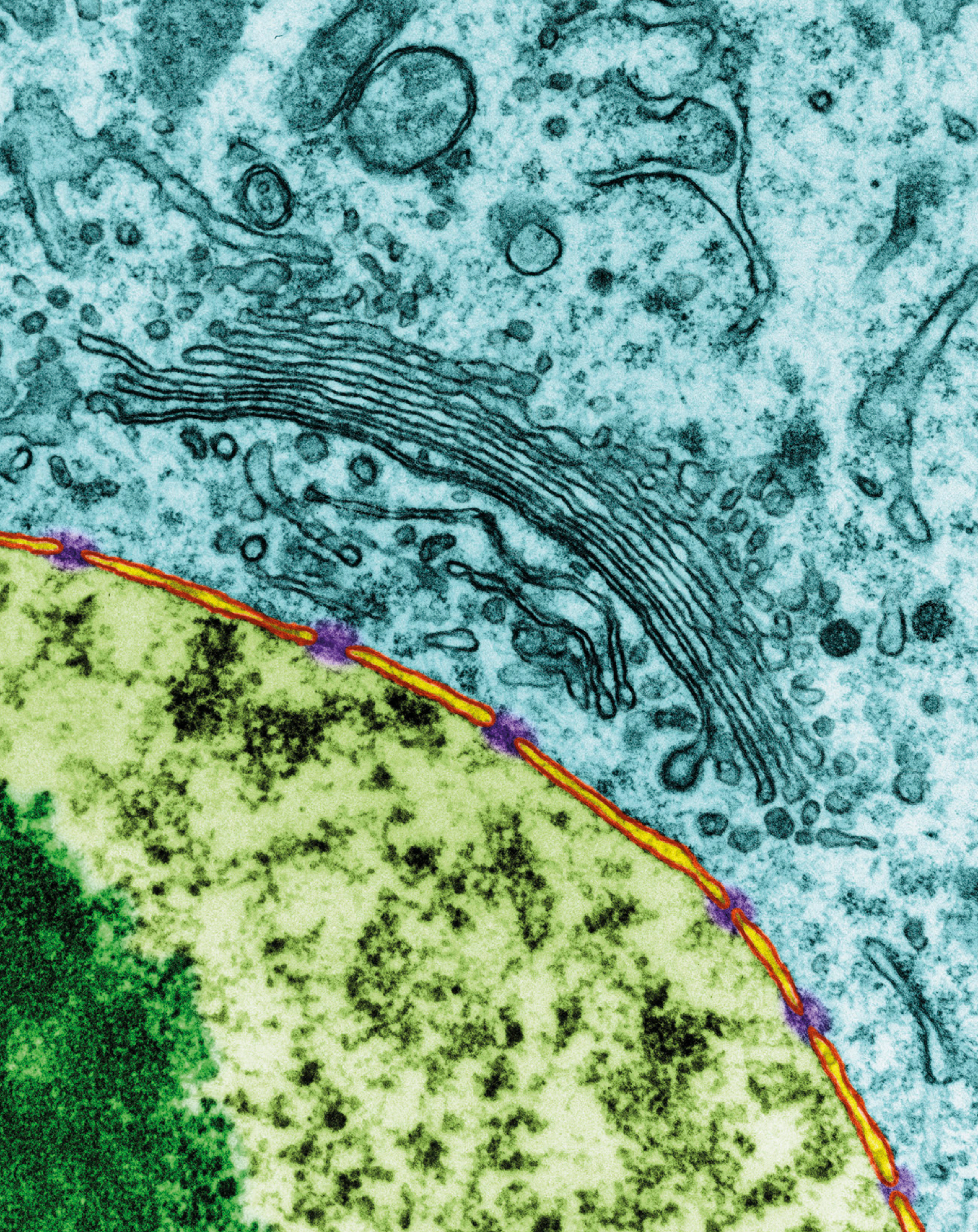
You will also be introduced to the study of microbiology and the tools that scientists use in this field. These tools will be used throughout the course to assist in making predictions and solving problems of a multidisciplinary nature.

Outcomes

By the end of this module you will be able to:

- conduct investigations to collect valid and reliable primary and secondary data and information BIO11-3
- select and process appropriate qualitative and quantitative data and information using a range of appropriate media BIO11-4
- describe single cells as the basis for all life by analysing and explaining cells' ultrastructure and biochemical processes BIO11-8





CHAPTER 02

Cell structure

This chapter examines the importance of cells as the basic units of life on Earth. You will learn about the different cellular structures of prokaryotic and eukaryotic cells by investigating various cell types and their organelles. A range of technologies used to examine and understand cell structures and functions, such as the electron microscope and synchrotron, will be explored. You will also investigate the fluid mosaic model of the cell membrane and learn about the important role the membrane plays in regulating the cellular environment.

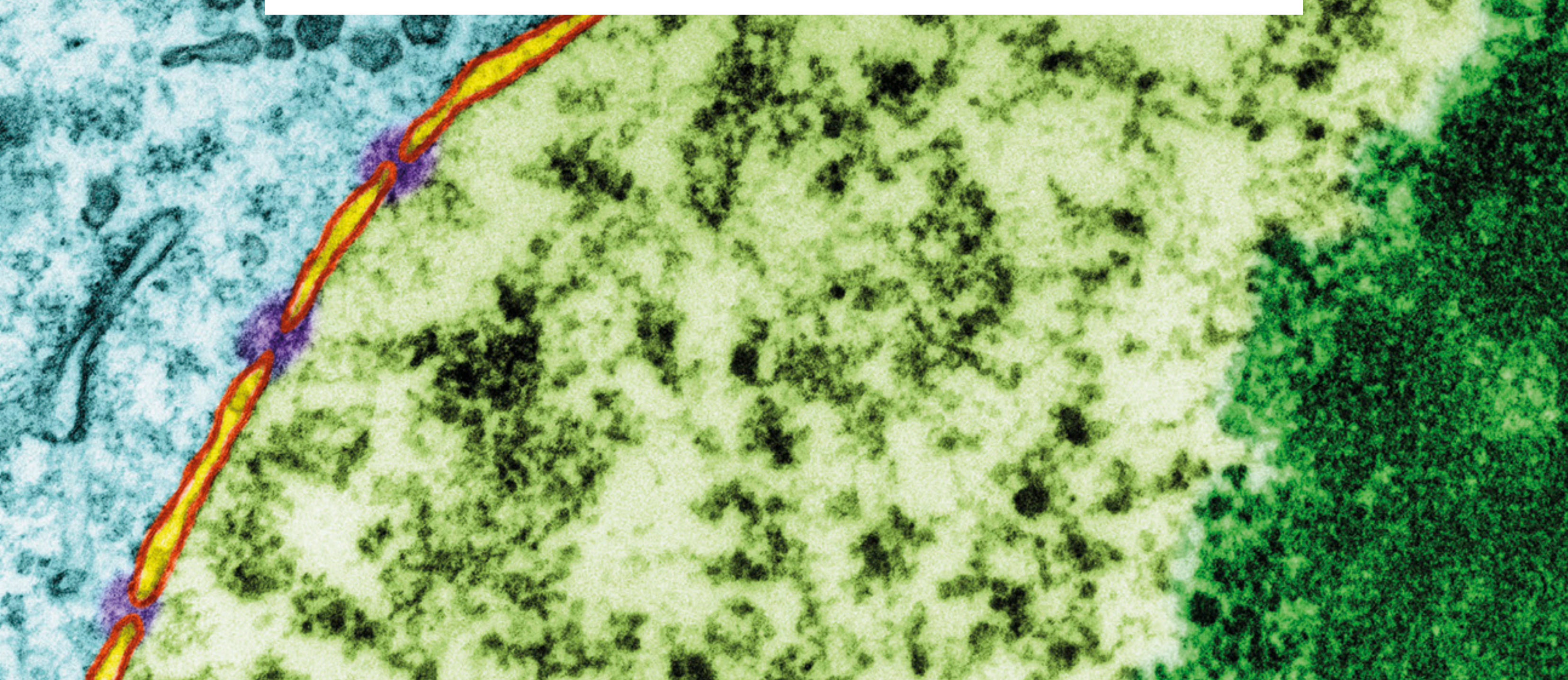
Content

INQUIRY QUESTION

What distinguishes one cell from another?

By the end of this chapter you will be able to:

- investigate different cellular structures, including but not limited to:
  - examining a variety of prokaryotic and eukaryotic cells (ACSBL032, ACSBL048) ICT
  - describing a range of technologies that are used to determine a cell's structure and function ICT
- investigate a variety of prokaryotic and eukaryotic cell structures, including but not limited to:
  - drawing scaled diagrams of a variety of cells (ACSBL035) ICT N
  - comparing and contrasting different cell organelles and arrangements CCT
  - modelling the structure and function of the fluid mosaic model of the cell membrane (ACSBL045) CCT ICT



2.1 Cell types

BIOLOGY INQUIRY CCT ICT

Building a cell

What distinguishes one cell from another?

COLLECT THIS…

- large sheet of paper
- coloured pens, pencils or craft supplies
- scissors
- sticky tape or tack
- tablet or computer to access the internet

DO THIS…

1. As a class, write the following terms on separate pieces of paper:
   - nucleus and DNA
   - ribosome
   - endoplasmic reticulum (rough and smooth)
   - Golgi apparatus
   - lysosome
   - mitochondrion
   - chloroplast
   - centriole
   - flagellum
   - vacuole
   - plastid
   - cell membrane
   - cell wall
2. Put the pieces of paper in a container.
3. Working in pairs, take one piece of paper from the container.
4. Take 10 minutes to research your selected organelle. Take note of its size and structure, its function and the cell type(s) it is found in (e.g. prokaryote or eukaryote). You will present this information to the class.
5. Draw or model your organelle to scale, using 1 micrometre/micron (μm) = 5 cm. If your organelle is found in both prokaryotic and eukaryotic cells, create one for a prokaryotic cell and one for a eukaryotic cell.
6. Working as a class, build a prokaryotic and eukaryotic cell by arranging your organelles on two large sheets of paper or cardboard.
7. As a pair, present the information about your organelle to the class.

RECORD THIS…

Describe the features that distinguish prokaryotic and eukaryotic cells.

Present information about each organelle in a table.

REFLECT ON THIS…

What distinguishes one cell from another?

Why do prokaryotic and eukaryotic cells have different structures?

How do these structures help prokaryotic and eukaryotic organisms function and survive?

WS 1.1

Cells are the basic structural units of all living things. In this section you will learn about the differences between prokaryotic and eukaryotic cells and the technologies used to view cell structures and understand their functions. Investigating a variety of cells and cell structures will allow you to compare organelles and their arrangements in cells. You will also learn about the composition of the cell membrane and the role it plays in cellular communication and transporting molecules in and out of cells.

COMMON CELL STRUCTURES

Cells are the basic structural unit of all living things. Although there are different types of cells, the cells of plants, animals and bacteria share a number of common structures (Figure 2.1.1). These include:

- a **cell membrane** (also known as the **plasma membrane**)—separates the interior of the cell from the outside environment
- **cytoplasm**—consists of the **cytosol** and, in **eukaryotes**, the **organelles**. Cytosol is a gel-like substance, made up of more than 80% water, and contains ions, salts and organic molecules
- **DNA**—carries hereditary information, directs the cell's activities and is passed from parents to offspring
- **ribosomes**—organelles responsible for the synthesis of **proteins**.

Proteins are large molecules composed of one or more polypeptides. Polypeptides are long, chain-like molecules consisting of many amino acids linked together.

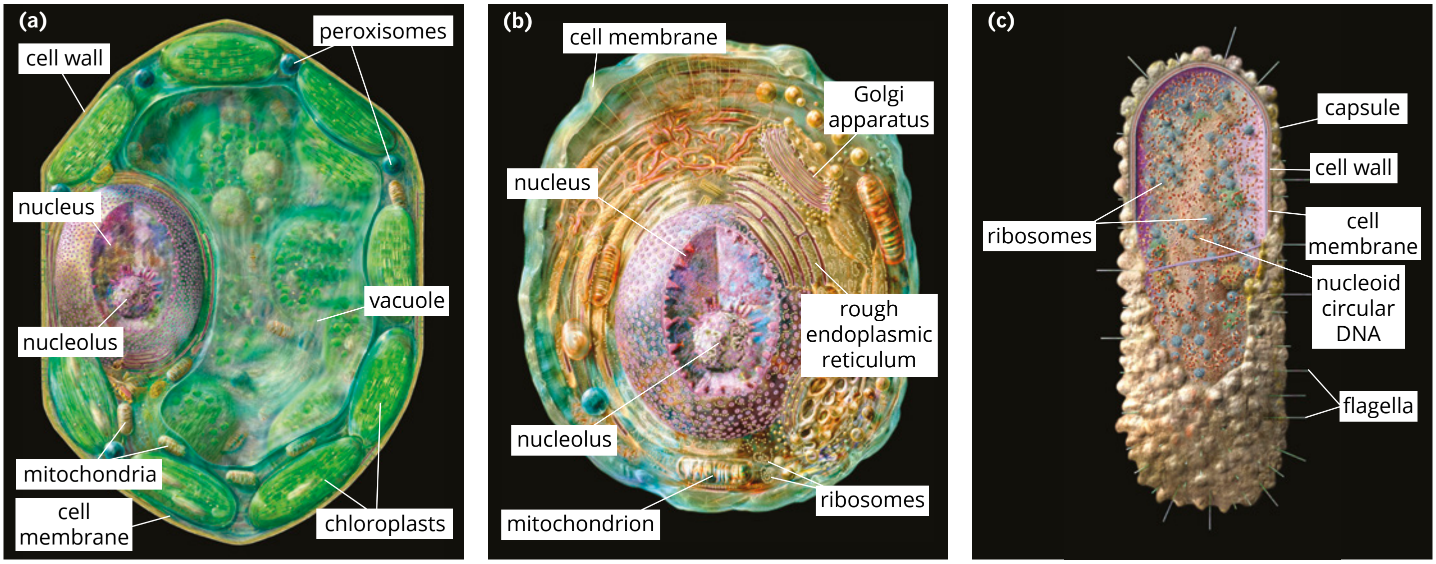


FIGURE 2.1.1 The cells in (a) plants, (b) animals and (c) bacteria share common structures, including a cell membrane, cytoplasm, DNA and ribosomes. Note: Not all structures are visible here.

CLASSIFICATION OF CELLS

There are two fundamentally different types of cells. Organisms are classified according to the cell type of which they are composed.

- **Prokaryotes** are composed of prokaryotic cells. They include bacteria and archaea. Prokaryotic cells are usually unicellular and are generally smaller and less complex than eukaryotic cells. The organelles of prokaryotic cells are not membrane-bound (Figure 2.1.2).
- Eukaryotes are composed of eukaryotic cells. They include protists, fungi, plants and animals. Eukaryotic cells contain membrane-bound organelles.

In older classification systems all organisms were divided into five ranks, called kingdoms. Prokaryotic organisms were placed in the kingdom Monera and eukaryotic organisms were placed in the kingdoms Protista, Plantae, Fungi and Animalia. These systems were based on the **morphology** (appearance and structure) of organisms.

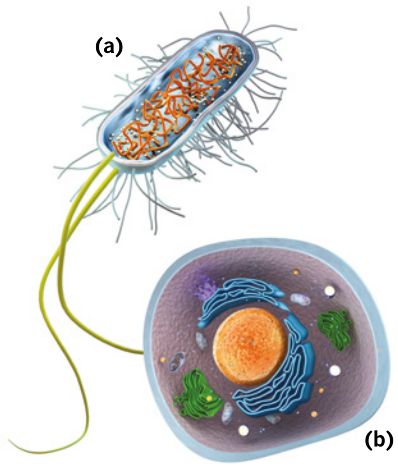


FIGURE 2.1.2 A typical (a) prokaryotic cell and (b) eukaryotic cell. Note the different membrane-bound organelles in the eukaryotic cell and the lack of such organelles in the prokaryotic cell.

In the late 1970s, the use of DNA techniques led to the discovery of two different types of prokaryotic cells. This discovery resulted in the development of a system with three domains and six kingdoms (Figure 2.1.3). **Domains** are now the highest rank in **taxonomy**, instead of kingdoms. Prokaryotes are divided into two domains: **Bacteria** and **Archaea**. All eukaryotic organisms are placed in a third domain called **Eukarya**. The four kingdoms within the Eukarya domain remain the same: Protista, Plantae, Fungi and Animalia (Figure 2.1.3).

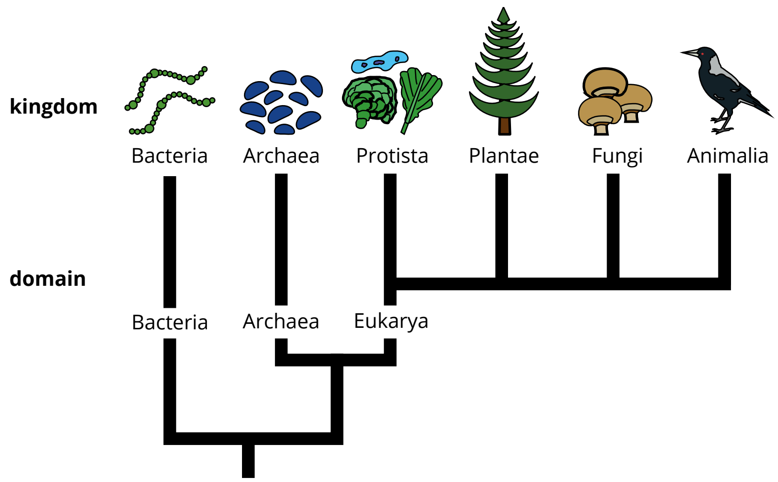


FIGURE 2.1.3 The classification of living things, showing the three domains based on cell types and the six kingdoms. Bacteria and Archaea have prokaryotic cells. Protista, Plantae, Fungi and Animalia have eukaryotic cells.

PROKARYOTES

Prokaryotes are organisms that are made up of a single cell (**unicellular**). Bacteria, cyanobacteria (photosynthetic bacteria), and archaea, such as methanogens, are examples of prokaryotes. Prokaryotic organisms can be found everywhere—even in extreme environments such as volcanoes.

Most prokaryotic cells are small and therefore have a large surface area relative to their volume. This allows the cells to take in and release materials efficiently and replicate quickly. You will learn about surface-area-to-volume ratio in Chapter 3.

GO TO ➤ Section 3.1 page 120

As the size of a cell decreases, the surface-area-to-volume ratio (SA:V) of the cell increases. A greater surface-area-to-volume ratio increases the rate at which materials can move across the surface. Being small allows cells to efficiently exchange materials with their environment.

The structure of a typical prokaryotic cell is shown in Figure 2.1.4. Prokaryote cells lack membrane-bound organelles, and their cytoplasm contains scattered ribosomes that are involved in the synthesis of proteins. The genetic material of prokaryotic cells is usually a single, circular DNA **chromosome** called the **genophore**, which is contained in an irregularly shaped region called the **nucleoid**. The nucleoid does not have a nuclear membrane like the **nucleus** of eukaryotes.

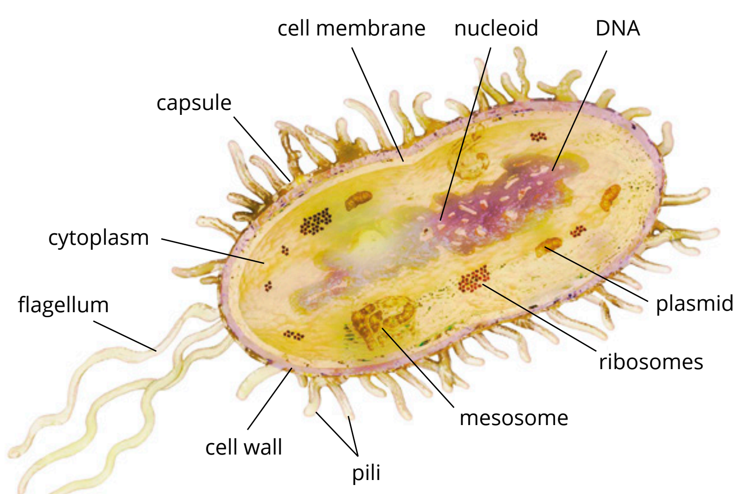


FIGURE 2.1.4 A typical prokaryotic bacterial cell

The prokaryotic chromosomal DNA is attached to the cell membrane by a region of the chromosome called the origin. In addition to this chromosomal DNA, many prokaryotic cells also contain small rings of double-stranded DNA called **plasmids**.

The cell membrane of prokaryotic cells is surrounded by an outer **cell wall**. Many bacteria also have a capsule outside the cell wall. The capsule protects the bacterial cell from damage, dehydration and engulfment by eukaryotic cells. It also helps the bacteria stick to surfaces. These features of bacterial capsules increase the virulence (ability to cause disease) of pathogenic bacteria.

Some prokaryotes can move around using a tail-like structure called a **flagellum**. Many prokaryotes have small hair-like projections called pili, which can also help to generate movement. Pili are also involved in the transfer of DNA between organisms. Specialised pili that can attach to surfaces are called **fimbriae**.

Bacteria

Most prokaryotes in the domain Bacteria are microscopic single-celled organisms. Fossil evidence dated to between 3.7 and 4.3 billion years old confirms that bacteria were the first type of living organism on Earth. Today they are still the most numerous type of organism in the biosphere.

Bacteria have very diverse **metabolic** systems, making them extremely adaptable. They can survive in almost every environment on Earth. Bacteria are common in moist, low-salt environments of moderate temperature, where sunlight or **organic compounds** are plentiful, and inside or on plants and animals.

Bacteria need little oxygen to survive, because they have many ways of extracting energy and fixing carbon. Bacteria can obtain energy from sunlight (**photosynthesis**) or by reducing **inorganic compounds** such as sulfides or ferrous ions (**chemosynthesis**).

Bacteria play an important role in ecosystems, because they break down many kinds of substances, including plant and animal remains and wastes. Bacteria are also widely used in industry to manufacture foods, such as cheeses and yoghurt, and in medicine, to produce antibiotics, drugs and even human insulin. Some bacteria can even break down oils and plastics, making them useful for pollution control.

> Prokaryotes are organisms with cells that do not have a nucleus surrounded by a membrane. They lack most other organelles. Bacterial cells are prokaryotic.

> Carbohydrates are organic compounds of carbon, hydrogen and oxygen, with the number of hydrogen and oxygen atoms in the ratio 2:1. This ratio of 2:1 is the same ratio of hydrogen to oxygen for water. Sugars and starches are examples of carbohydrates.

Gram-positive and gram-negative bacteria

Bacteria have mesh-like cell walls that are made up of a polymer called **peptidoglycan** (also known as murein). Different species of bacteria have different cell wall characteristics. Based on the structure of their cell walls, different species of bacteria can be classified as **gram-positive** or **gram-negative** using a technique called Gram staining.

Gram staining involves adding a purple dye called crystal violet to bacterial cells. The dye interacts differently with the cell walls of gram-positive and gram-negative bacteria, staining the cells different colours. Gram-positive bacteria have a thicker layer of peptidoglycan that absorbs and holds the stain, so they give a purple or 'positive' result. Gram-negative bacteria have a much thinner layer of peptidoglycan that does not retain the stain as well, so they give a pink or 'negative' result (Figure 2.1.5).

FIGURE 2.1.5 Gram-positive bacteria (stained purple) and gram-negative bacteria (stained pink). This light micrograph (LM) was produced using a light microscope.

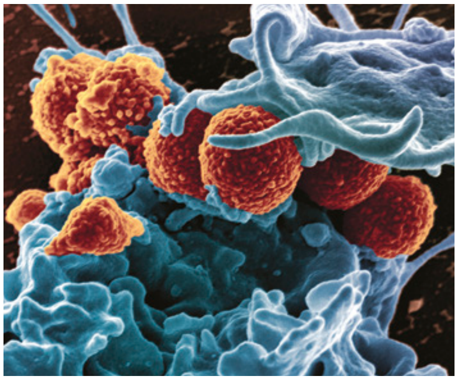


FIGURE 2.1.6 *Staphylococcus aureus* (commonly called golden staph) being engulfed by a white blood cell. *S. aureus* are gram-positive bacteria that can cause serious infections in humans. This image was produced using a scanning electron microscope (SEM).

There are numerous types of gram-negative and gram-positive bacteria. For example, gram-positive cocci are spherical bacteria that include *Staphylococcus* and *Streptococcus*, which can cause serious diseases or death in humans (Figure 2.1.6). An example of a gram-negative bacterium is a cyanobacterium (Figure 2.1.7a). Cyanobacteria were once called blue-green algae because they contain chlorophyll. We now know that cyanobacteria are actually prokaryotes, and so they are placed in the Bacteria domain. Cyanobacteria often form dense colonies in shallow estuaries or fresh water (Figure 2.1.7b). Some species form large colonies, known as blooms, which produce toxins. These toxic blooms can kill fish and other aquatic life and cause illness in humans.

FIGURE 2.1.7 (a) Gram-negative cyanobacteria, *Synechococcus cyanobacterium* (SEM), and (b) a colony of *S. cyanobacteria* in a lake

Archaea

The prokaryotes in the domain Archaea include **extremophiles**. These are organisms that can live in extreme conditions, such as:

- areas of high temperatures (thermophiles)
- areas of low temperatures
- the upper atmosphere
- alkaline environments
- acidic environments (acidophiles)
- salty environments (halophiles)
- environments with little or no oxygen
- areas without light
- petroleum deposits deep underground.

Archaea hold records for living in the hottest places (121°C), the most acidic environments (pH 0), and the saltiest water (about 30% salt). However, some archaea live in less extreme environments such as the open seas. There are many different types of extremophiles. Hyperthermophiles such as *Pyrococcus furiosus* can survive in very hot environments such as undersea vents, where temperatures are often above 100°C (Figure 2.1.8). They can also withstand extremely high pressures. *Sulfolobus* is a genus of archaea that live in volcanic springs. *Sulfolobus* are thermophiles as well as acidophiles, because they can survive in both high temperatures and high acidity (Figure 2.1.9).

Although archaea and bacteria are now known to be very different organisms, scientists did not recognise these groups as distinct for a long time. Many species of archaea and bacteria look very similar. The extreme habitats that archaea occupy also make them difficult to find and culture in a laboratory.

The ability of archaea to live in extreme environments is due in part to their unique cell membranes. Like other living organisms, archaea possess a cell membrane composed mainly of **lipids**. Cell membranes need to be fluid to enable cells to rapidly respond to external conditions and allow proteins to easily move in and out of cells. You will learn more about the structure of cell membranes in Section 2.3.

The lipids that compose the cell membranes of archaea are different from the lipids in eukaryotic cell membranes. The cell membranes of archaea form a unique structure that remains fluid and selectively **permeable (semipermeable)** over a wide range of temperatures—from freezing cold to boiling hot. The lipids in eukaryotic cell membranes have fluidity and selective permeability, but only in a narrow range of temperatures.

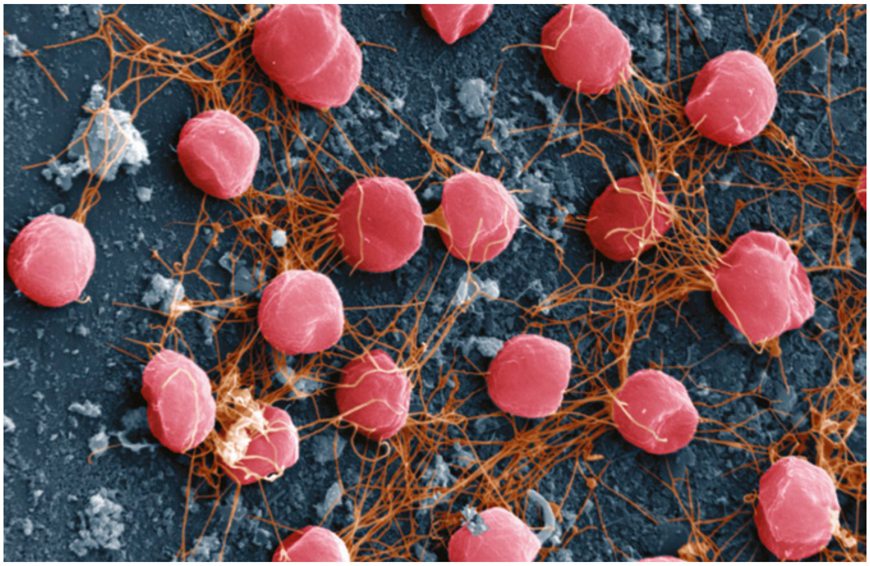


FIGURE 2.1.8 A hyperthermophile called *Pyrococcus furiosus*. This species of archaea can only exist in very hot environments, such as hot undersea vents.

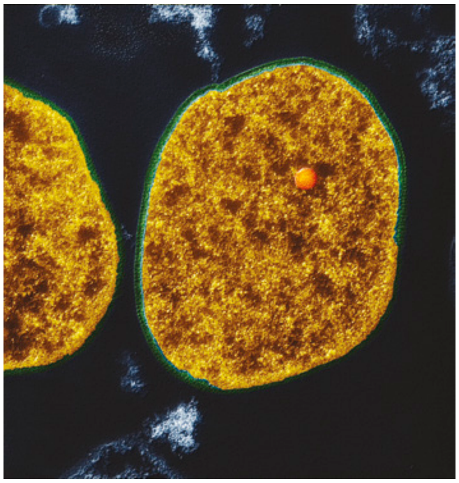


FIGURE 2.1.9 *Sulfolobus* microorganisms are thermophiles as well as acidophiles. This genus of archaea thrive in hot, acidic environments.

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Lipids are 'fatty' organic compounds, including fats and oils, which are composed mainly of carbon, hydrogen and oxygen. Lipids have proportionally less oxygen than carbohydrates, and may contain other elements.

Differences between bacteria and archaea

Despite their name, archaea are not the most ancient group of organisms. DNA studies have shown that bacteria are the most ancient group, and that archaea evolved from eukaryotic cells at a later time.

The cells of bacteria and archaea are different in several ways:

- Archaea have a different type of lipid structure in the cell membrane.
- The cell wall in bacteria contains peptidoglycan, but the cell wall in archaea does not (although there is a similar compound in some archaea).
- Both have diverse metabolic systems, but methanogenesis (in which methane is produced) is unique to archaea.

EUKARYOTES

The cells of eukaryotes are much larger and more complex than prokaryotic cells (Table 2.1.1). Eukaryotic cells have a cell (plasma) membrane that surrounds the cell's cytoplasm and internal (non-plasma) membranes that form specialised compartments within the cell. The membrane-bound structures in eukaryotic cells are called organelles. Cell compartmentalisation and organelles will be discussed further in Section 2.2.

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Eukaryotic organisms are incredibly diverse. There are unicellular and **multicellular** forms and organisms that can reproduce asexually and sexually. Multicellularity and sexual reproduction are unique to eukaryotes. Eukaryotic organisms only represent a small proportion of all species on Earth, but because eukaryotes are much larger in size, their total biomass is about the same as that of prokaryotes.

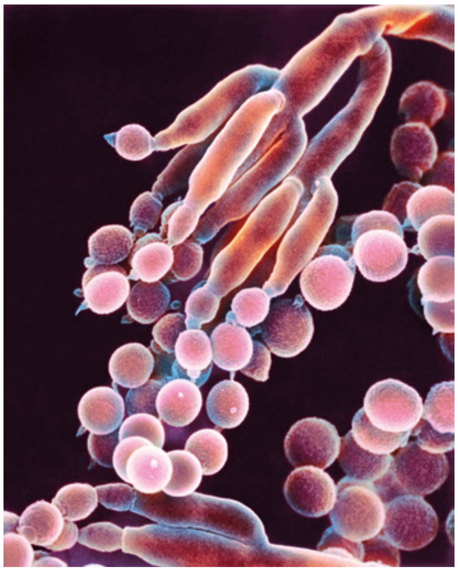


FIGURE 2.1.10 The reproductive cells (spores) of a penicillin fungus (*Penicillium chrysogenum*). Coloured SEM, magnification: x1750

Eukaryotes are divided into the four kingdoms, Protista, Fungi, Plantae and Animalia. The cells of these groups share many typical eukaryotic features, but they also have cell structures and functions that are unique (Figures 2.1.10 and 2.1.11).

Animal and plant cells

Different groups of eukaryotic organisms can have different cellular structures. The organelles are involved in specific cellular functions, so their presence depends on the needs of the cells. A good way to understand this is to compare animal and plant cells.

Animal and plant cells are very similar. They both contain a nucleus surrounded by cytoplasm, which is enclosed by the cell membrane. They have **mitochondria** (singular mitochondrion) for **cellular respiration**, and organelles, such as the **Golgi apparatus**, in which proteins are synthesised and processed. However, plant and animal cells also differ in several ways (Figure 2.1.11 and Table 2.1.2):

- Plant cells have cell walls made from cellulose outside the cell membrane. The cell wall provides structural support and results in a fixed shape. Animal cells do not have cell walls.
- Plant cells have a large, permanent **vacuole** that stores minerals and nutrients in a solution called cell sap. The vacuole also provides structure to plant cells by maintaining **turgor** pressure against the cell wall. Animal cells have many small temporary fluid-filled vacuoles called vesicles, but these do not provide structural support.
- Plant cells have **chloroplasts**, which are the site of photosynthesis. Animal cells do not contain chloroplasts and do not perform photosynthesis.

FIGURE 2.1.11 Larva of a small crustacean (copepod) (centre right) among freshwater phytoplankton. Seen here are golden algae (*Synura* sp.) and green algae (*Pandorina morum*). LM, magnification: x178

COMPARISON OF PROKARYOTIC AND EUKARYOTIC CELLS

Prokaryotic and eukaryotic cells differ in several ways (Table 2.1.1 and Table 2.1.2):

- Prokaryotic cells do not have membrane-bound organelles, while eukaryotic cells have many different membrane-bound organelles, with specialised structures and functions.
- Prokaryotic cells do not have a nucleus, and their DNA is in the form of a single, circular chromosome and small, circular molecules called plasmids. The DNA of eukaryotic cells is in the form of linear chromosomes and is contained in the nucleus.
- Prokaryotic cell walls are made of peptidoglycan. The cells of some eukaryotes, such as plants, **fungi** (singular fungus) and **protists**, are surrounded by a cell wall composed of **carbohydrates**.
- Prokaryotic and eukaryotic cells also differ significantly in size. The typical eukaryotic cell is around 10 times larger than most prokaryotic cells.

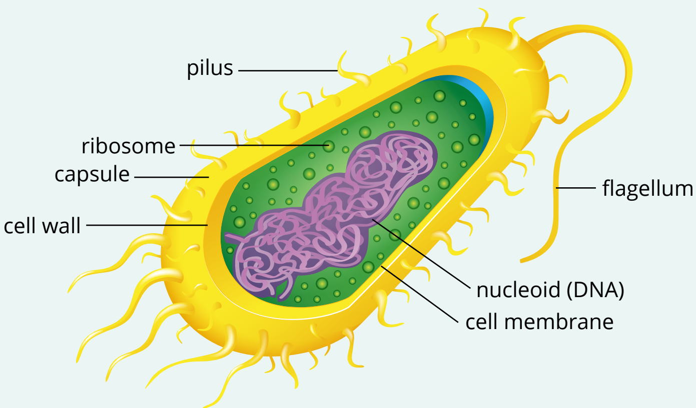
TABLE 2.1.1 Comparison of prokaryotic and eukaryotic cells

Feature	Prokaryotic cells	Eukaryotic cells
size	• very small (0.1 to 5.0 μm)	• larger, with large variation in size (10 to 100 μm)
surface-area-to-volume ratio (SA:V)	• large SA:V ratio • allows materials to diffuse in and out of the cell rapidly	• smaller SA:V ratio • results in slower diffusion
membrane-bound organelles	• absent, no membrane-bound organelles	• many organelles bound by membranes, forming an organised internal structure
chromosomal DNA	• a single circular chromosome and small circular DNA molecules called plasmids • located in a region of cytoplasm called the nucleoid, lacking a membrane	• linear chromosomes • located in the nucleus, which is separated from the cytoplasm by a double-layered membrane
ribosomes	• many tiny ribosomes scattered throughout the cytoplasm	• many ribosomes, either attached to the endoplasmic reticulum, or free in the cytoplasm
cell membrane	• bilayer of phospholipid molecules enclosing the cytoplasm in bacteria • phospholipids in archaea are different and sometimes fuse into a monolayer	• bilayer of phospholipid molecules enclosing the cytoplasm
cell wall	• in bacteria, consists of protein/carbohydrate compound called peptidoglycan • in archaea, the cell wall is composed of surface-layer proteins that form a rigid layer	• present in fungi, plants and some protists • mainly made of carbohydrates: chitin in fungi and cellulose in plants
flagella	• may have flagella to provide movement • consists of three protein fibrils coiled in a helix and protruding through the cell membrane and wall	• may have flagella or cilia (fine hair-like projections) for motility (but not in fungi) • consists of a highly organised array of microtubules (hollow protein tubes) enclosed by extended cell membrane

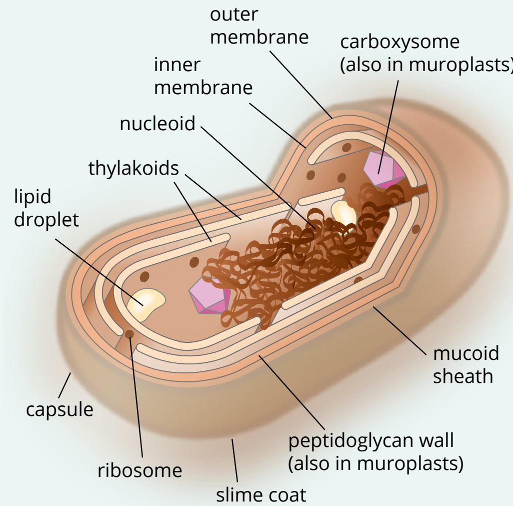
TABLE 2.1.2 Diagrams of prokaryotic cells, bacteria, archaea and cyanobacteria, and eukaryotic cells of fungi, protist, plant and animal, showing the organelles visible under an electron microscope

Prokaryotes

Bacteria and archaea

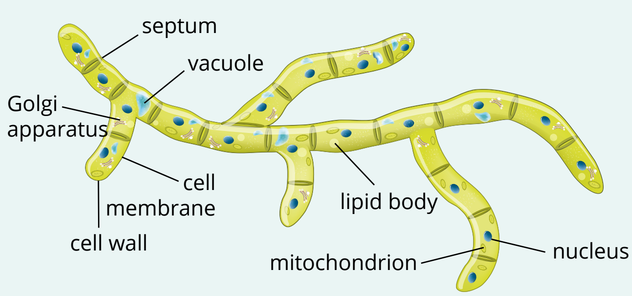


Cyanobacteria

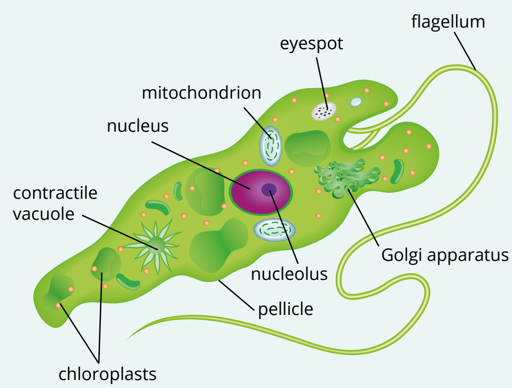


Eukaryotes

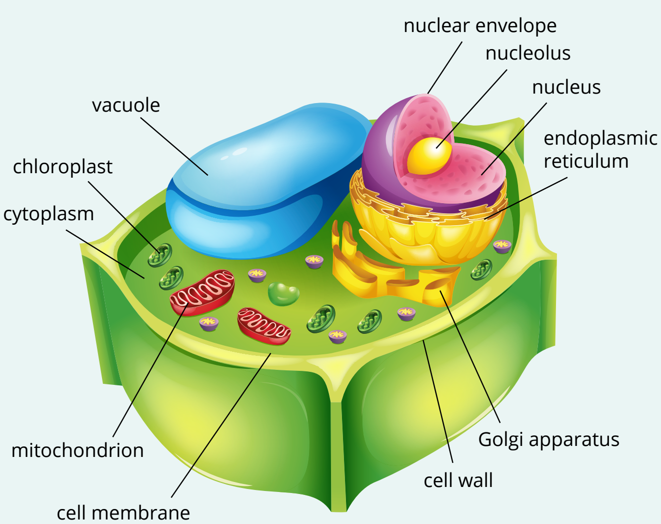
Fungi



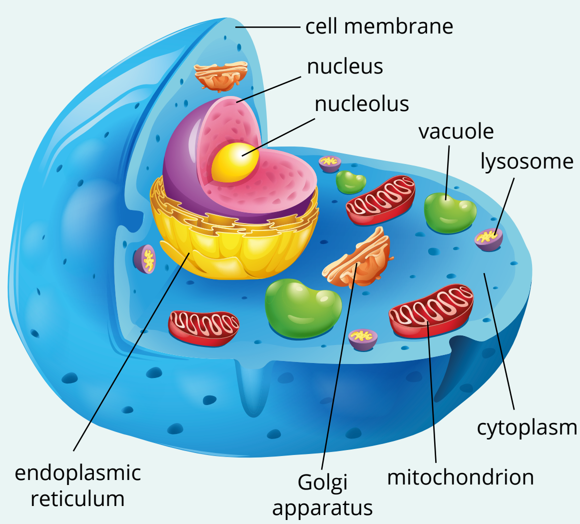
Protist



Plant



Animal



2.1 Review

SUMMARY

- There are two fundamentally different types of cells: prokaryotic and eukaryotic.
- Organisms with prokaryotic cells are called prokaryotes. They are classified into two domains: Bacteria and Archaea.
- Prokaryotic cells are small, with simple structures. They lack membrane-bound organelles and have DNA in a circular chromosome.
- Archaea (extremophiles) are often found in very harsh environments, and are protected by their unique cell membrane structure.
- Organisms with eukaryotic cells are called eukaryotes. They are classified into the domain Eukarya, which is divided into four kingdoms: Protista, Fungi, Plantae and Animalia.
- Eukaryotic cells have a complex structure. They have many membrane-bound organelles in the cytoplasm, and linear DNA in a membrane-bound nucleus.
- All cells have a cell membrane (also known as a plasma membrane), cytoplasm, genetic material in the form of DNA, and ribosomes.

KEY QUESTIONS

1 What are the three domains in which all life is classified?

2 What feature does all life on Earth share?

3 Describe three structures that distinguish prokaryotic and eukaryotic cells.

4 Why are archaea also known as extremophiles?

5 What property of archaean cell walls allows them to be extremophiles?

6 Select the statement that correctly describes features that are unique to eukaryotes.

A asexual reproduction and cell walls
B sexual reproduction and DNA
C multicellularity and sexual reproduction
D cytoplasm and multicellularity

7 Name two structures that are unique to plant cells.

2.2 Cell organelles

In the previous section, you learnt that the two fundamentally different types of cells are prokaryotic and eukaryotic cells, and that organisms are classified into one of three domains (Bacteria, Archaea or Eukarya) according to the type of cell they have.

Bacteria and archaea are prokaryotes: their cells do not contain membrane-bound organelles. Animals, plants, fungi and protists are eukaryotes. Each represents a kingdom in taxonomy: Animalia, Plantae, Fungi and Protista. There are many different types of cells within the four eukaryotic kingdoms. Although these cells have very different appearances and functions, they all contain membrane-bound organelles (Figure 2.2.1).

In this section, you will learn about the importance of cell compartmentalisation and membrane-bound structures in eukaryotes. You will also learn more about the structure and function of organelles and the differences between plant and animal cells.

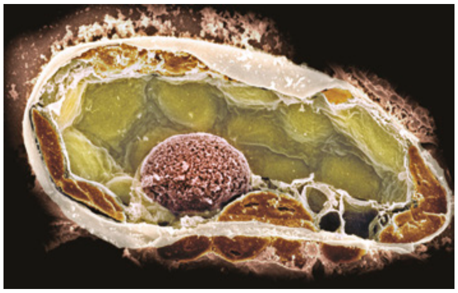


FIGURE 2.2.1 Plants are eukaryotes and so their cells have membrane-bound structures, some of which can be seen in this SEM image. The cell is encased in a cell wall made of cellulose, hemicellulose and pectin. Inside the cell are chloroplasts (green), the nucleus (pink) and a large vacuole in the centre.

COMPARTMENTALISATION IN EUKARYOTIC CELLS

As you learnt in the previous section, the two main types of cells are prokaryotic and eukaryotic cells.

- Prokaryotic cells are relatively small and lack membrane-bound organelles. Bacteria and archaea are prokaryotes.
- Eukaryotic cells are relatively large and more complex. They possess membrane-bound organelles such as a nucleus and mitochondria. Protists, fungi, plants and animals are called eukaryotes because they are composed of eukaryotic cells.

As well as a cell membrane surrounding the cytoplasm, eukaryotes have internal membranes that form specialised membrane-bound compartments within the cell. This is known as **cell compartmentalisation**. The membrane-bound compartments are called organelles. However, not all organelles have membranes (Figure 2.2.2).

Each membrane-bound organelle has a different function. For this reason, each organelle requires a different internal composition, including a high concentration of **enzymes** and reactants that are needed for the organelle's particular function.

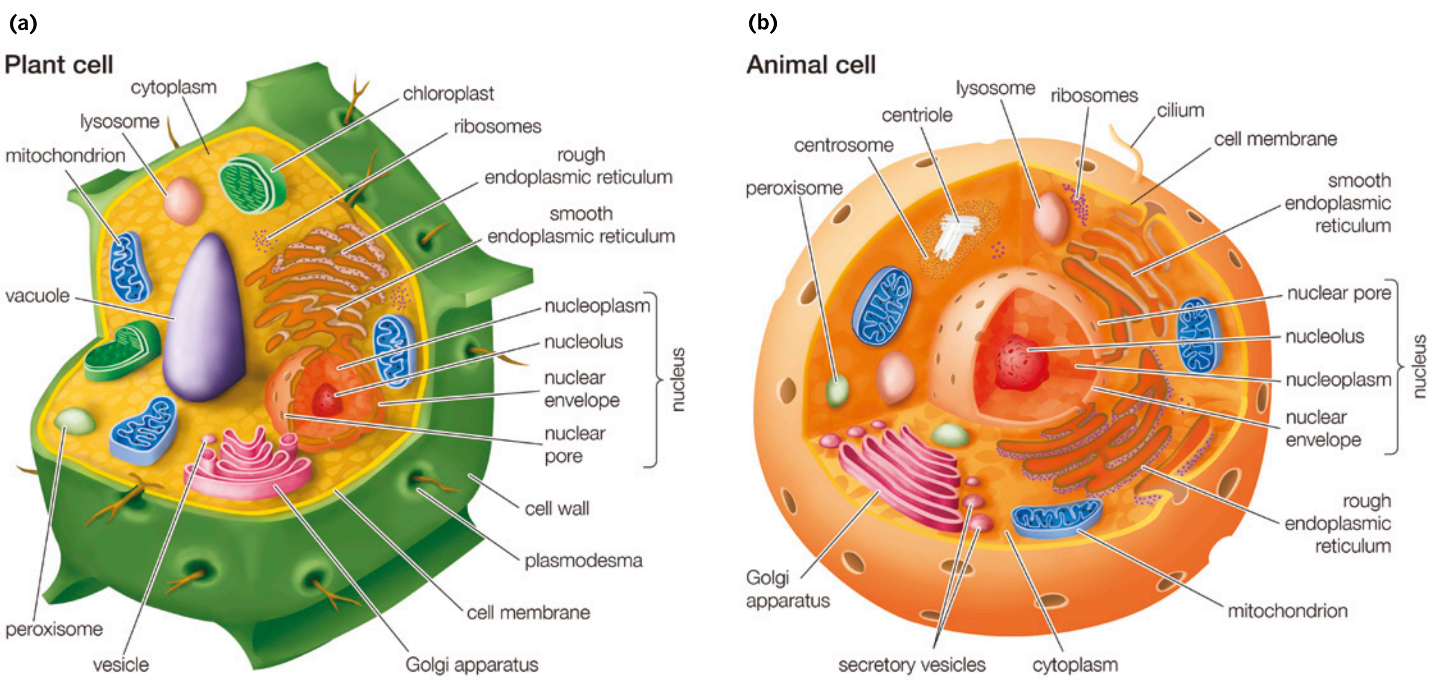


FIGURE 2.2.2 The many membrane-bound organelles of eukaryotic cells can be seen in these illustrations of (a) a plant and (b) an animal cell.

Role of organelle membranes

The membranes surrounding organelles control the movement of substances between the organelle and the cell's cytosol (the liquid part of the cytoplasm). The outer cell membrane enables the cytosol to have a different composition from the cell's surrounding environment. In the same way, membranes of membrane-bound organelles enable each organelle to have a different composition from the surrounding cytosol and other organelles.

Benefits of compartmentalisation

Cellular compartmentalisation benefits the cell by:

- allowing enzymes and reactants for a particular cellular function to be close together in high concentrations and at the right conditions, such as at optimum pH levels, so that the processes within the organelles are very efficient
- allowing processes that require different environments to occur at the same time, in the same cell
- making the cell less vulnerable to changes to its external environment, because any changes will affect the cytosol much more than the membrane-bound organelles.

Enzymes are proteins that act as biological catalysts. Enzymes speed up rates of biochemical reactions that would otherwise take place much more slowly. Their action is specific: they catalyse (cause or accelerate) only one type of reaction.

BIOLOGY IN ACTION ICT

An artificial cell with working organelles

Cells are the basic building blocks of all life on Earth. These microscopic structures are responsible for carrying out all the processes that make life possible—everything from transporting oxygen, nutrients and waste to synthesising proteins and producing new life.

Cells are extremely complex, yet incredibly efficient. They can process multiple reactions simultaneously in a very small space. The efficiency of eukaryotic cells is due to compartmentalisation. Having the cell organised into compartments allows processes that require different environments to occur at the same time, in the same cell. The cell sends chemical messages, called signals, between the compartments to ensure that the cell is functioning optimally as a unit.

Biochemists are interested in understanding how a cell can carry out such efficient chemistry on such a small scale. But the complexity of cells makes it extremely difficult for scientists to mimic these structures and their functions in the laboratory. If scientists can create functioning cell-like structures in the laboratory, they can learn more about the inner workings of cells. This will help them better understand how life evolved from chemical reactions to functioning organisms.

In 2014, a team of researchers from the University of Bordeaux in France and Radboud University in the Netherlands built the world's first artificial eukaryotic cell. The scientists created the cell's organelles from tiny, enzyme-filled spheres. The organelles were placed inside a droplet of water, which was then coated with a polymer layer to create a cell membrane (Figure 2.2.3). To test whether the artificial cell was functional, the researchers used fluorescent dyes to observe the series of chemical reactions within it. Just like the cells in our bodies, chemical reactions took place in the organelles, and the products of these reactions then moved into the cell membrane for processing elsewhere.

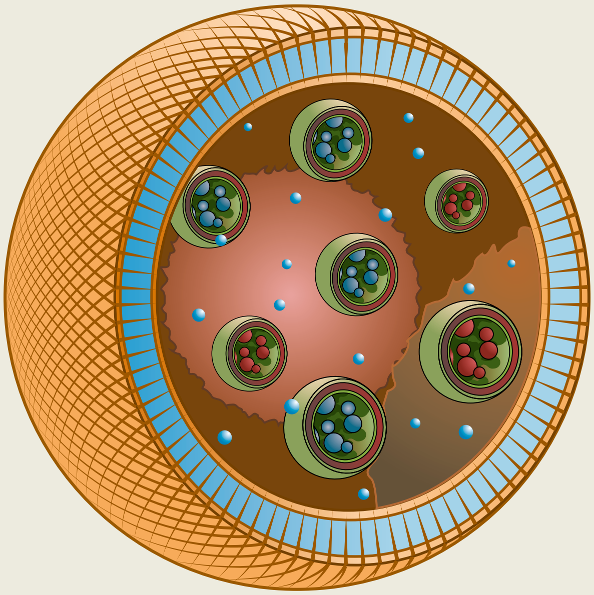


FIGURE 2.2.3 This cutaway diagram of an artificial cell shows a polymer membrane surrounding a water droplet containing enzyme-filled spheres that function as organelles.

MEMBRANE-BOUND AND NON-MEMBRANE-BOUND ORGANELLES

Organelles are subcellular structures that have specific functions within the cell (Table 2.2.1). Some organelles, as previously mentioned, are membrane-bound compartments within the cytoplasm. Membrane-bound organelles are only present in eukaryotic cells.

Prokaryotic cells have some non-membrane-bound organelles, such as ribosomes, a cell wall and sometimes flagella, although the structure and composition of these are usually different from those of eukaryotic cells.

TABLE 2.2.1 Organelle structure and function

Organelle	Structure	Function
nucleus	• membrane-bound: double membrane • contains DNA	contains the genetic instructions for cell replication, growth, repair and function
ribosome	• made of proteins and rRNA • no membrane	synthesises proteins
rough endoplasmic reticulum	• membrane-bound network of cisternae (membraneous sacs) • ribosomes bind to its membranes, giving it a ‘rough’ appearance	processes and modifies proteins
smooth endoplasmic reticulum	• membrane-bound network of cisternae	synthesises lipids
Golgi apparatus	• membrane-bound stack of cisternae that are not connected to each other	processes and packages proteins
lysosome	• membrane-bound vesicle containing digestive enzymes	digests cellular waste material and foreign matter
mitochondrion	• membrane-bound: double membrane, inner membrane is highly folded • contains DNA	obtains energy from organic compounds
chloroplast	• spherical or ellipsoidal, with double membrane • contains DNA and thylakoid sacs	uses light energy, carbon dioxide and water to produce glucose
centriole	• small structure in the cytoplasm, consisting of microtubules	involved in cell division and the formation of cell structures such as flagella and cilia
cilium or flagellum	• external structure consisting of microtubules	motility; movement of substances across cell surface
vacuole	• membrane-bound, fluid-filled vesicle	stores substances; also involved in cell structure in plant cells
plastid	• small, with double membrane • contains DNA	synthesises and stores various organic molecules
cell wall	• external structure surrounding cell membrane • composition depends on type of cell • no membrane	cell structure and protection

FUNCTION AND ULTRASTRUCTURE OF ORGANELLES

Cellular organelles are involved in several different functions (Table 2.2.2). These include protein and lipid synthesis and processing, energy transformation, storage and maintaining cell structure.

TABLE 2.2.2 Organelles and their functions

Function	Organelle	Present in plants	Present in animals
synthesis and processing of proteins and lipids	nucleus	√	√
	ribosome	√	√
	rough endoplasmic reticulum	√	√
	smooth endoplasmic reticulum	√	√
	Golgi apparatus	√	√
	lysosome	sometimes	√
energy transformations	mitochondrion	√	√
	chloroplast	√	×
storage and cell structure	vacuole	√	small
	plastid	√	×
	cell wall	√	×
	cytoskeleton	√	√
	centriole	sometimes	√
	cilium or flagellum	√	√

Synthesis and processing of proteins and lipids

Organelles involved in the synthesis and processing of proteins and lipids in eukaryotic cells are the nucleus, ribosomes, endoplasmic reticulum, Golgi apparatus and lysosomes.

Nucleus

In eukaryotes, the nucleus is a large organelle surrounded by a double-layered nuclear membrane. The nuclear membrane contains pores that link it with the cytosol (Figure 2.2.4). The nucleus contains most of the genetic material, which is formed in linear chromosomes composed of DNA and proteins. Chromosomes are usually not clearly visible, except during cell division. The most visible structure inside the nucleus of a non-dividing cell is the **nucleolus**. The nucleolus is composed of proteins, DNA and **RNA**, and is where ribosomes are assembled.

The information for the synthesis of new proteins is present in genes within the DNA. The genes are transcribed from the DNA into copies known as messenger RNA (**mRNA**). The mRNA travels through the nuclear membrane's pores into the cytosol and to the ribosomes, where the new proteins are made.

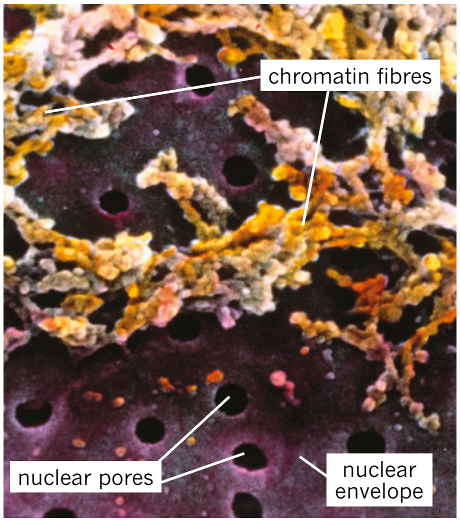


FIGURE 2.2.4 The nuclear envelope of an onion root tip cell (SEM). The envelope consists of a double membrane (purple), which encloses the nuclear DNA. The nuclear pores (black circles) are pathways for the transport of larger molecules between the nucleus and the cytosol. Contained within the nucleus are the chromatin fibres (yellow and orange), which consists of DNA, RNA and protein.

Ribosomes

Cells contain many thousands of ribosomes. These are only about 30 nanometres (nm) in diameter, and can therefore only be seen under an electron microscope. Ribosomes are composed of proteins and ribosomal RNA (**rRNA**), and are the sites of protein synthesis. They translate the sequence of amino acids specified by the mRNA into proteins. Ribosomes do not have a membrane surrounding them; they are non-membrane-bound organelles.

Ribosomes consist of two subunits joined together (Figure 2.2.5). The subunits in eukaryote ribosomes are different from those in prokaryote ribosomes.

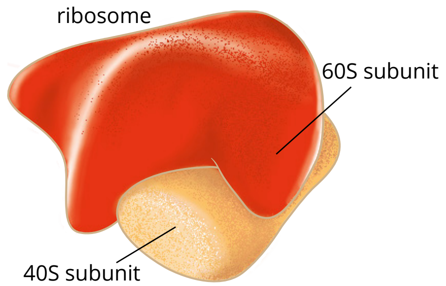


FIGURE 2.2.5 A single eukaryote ribosome consists of a larger 60S subunit and a smaller 40S subunit, which together form an 80S unit.

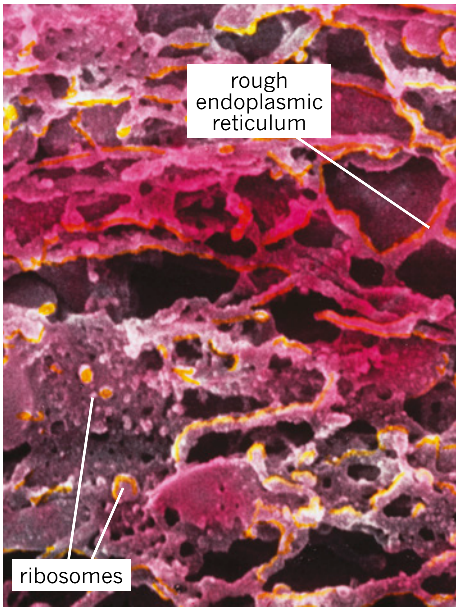


FIGURE 2.2.6 Endoplasmic reticulum in an olfactory epithelium supporting cell (SEM). Endoplasmic reticulum is a network of folded membranes forming sheets, tubes or flattened sacs in the cell cytosol. On the surface of some of the endoplasmic reticulum membranes are ribosomes (yellow spheres). Endoplasmic reticulum with ribosomes bound to it is known as rough endoplasmic reticulum.

Ribosomes are found either free in the cytosol, or bound to endoplasmic reticulum. When ribosomes are bound to the endoplasmic reticulum, it is called the **rough endoplasmic reticulum**. Proteins produced in free ribosomes will function in the cell's cytosol, while proteins synthesised in ribosomes bound to the endoplasmic reticulum are secreted out of the cell, packaged into organelles or inserted into cell membranes.

Endoplasmic reticulum

The endoplasmic reticulum is a network of intracellular membranous sacs (**cisternae**) and tubules. It links with the cell membrane and other membranous organelles, including the nucleus.

The endoplasmic reticulum can be rough or smooth. Rough endoplasmic reticulum has ribosomes attached (Figure 2.2.6). After the ribosomes have translated mRNA into proteins, the proteins pass into the endoplasmic reticulum cavity, which contains enzymes. The enzymes add sugar molecules to the proteins to form glycoproteins. Rough endoplasmic reticulum is abundant in cells that actively produce and export proteins, such as pancreatic cells, which secrete digestive enzymes. From the rough endoplasmic reticulum, proteins move into the Golgi apparatus for export from the cell.

Smooth endoplasmic reticulum does not have ribosomes attached. It contains the enzymes involved in the synthesis of molecules other than proteins, such as **phospholipids** and steroids. Smooth endoplasmic reticulum is abundant in steroid-secreting cells in the testes, ovaries, kidneys and adrenal glands (Figure 2.2.7).

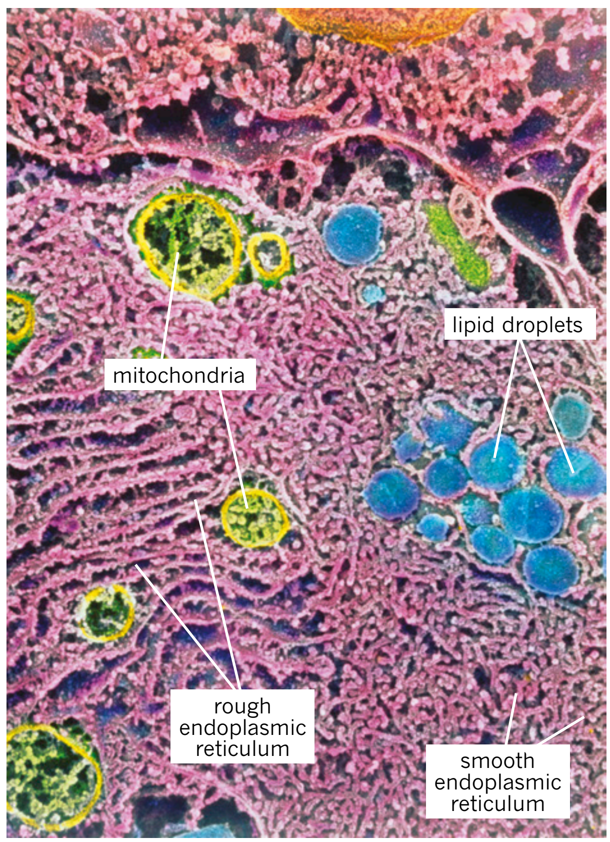


FIGURE 2.2.7 Smooth (right) and rough (left) endoplasmic reticulum inside a Leydig cell of a 14-week-old human fetus (SEM). Leydig cells synthesise steroid hormones in the male testis. Lipid droplets (round, blue structures) supply the cholesterol needed for the biosynthesis of steroids. Mitochondria (yellow) produce chemical energy for the cell.

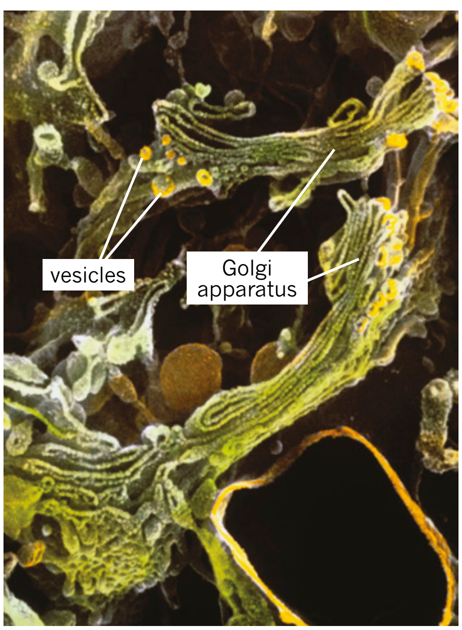


FIGURE 2.2.8 The Golgi apparatus of an olfactory bulb cell (SEM). The Golgi apparatus consists of a stack of flattened, interconnecting, membranous sacs (centre right and upper centre). Biochemicals are packaged into swellings at the margins of the sacs and become pinched off as vesicles (small, yellow spheres).

Golgi apparatus

The Golgi apparatus is also called the Golgi body or Golgi complex. It is a stack of flattened, smooth membrane sacs called cisternae (Figure 2.2.8).

Unlike the cisternae found in the rough endoplasmic reticulum, the cisternae in the Golgi apparatus are not connected. When proteins formed in the rough endoplasmic reticulum reach the Golgi apparatus, vesicles are formed from each cisternae. The vesicles transport the proteins from one cisternae to the next, where they are modified for use by the cell, or for transport out of the cell.

The cisternae then form transport vesicles to move the modified proteins into the cytosol, into other organelles, or out of the cell. For example, digestive enzymes sent to **lysosomes** are not released from the cell, while secreted hormones are exported from the cell. Other vesicles budding from the Golgi apparatus carry membrane-bound proteins to the cell membrane.

The Golgi apparatus has two faces: the ***cis* face** and the ***trans* face** (Figure 2.2.9). The cisternae of the *cis* face are connected to the endoplasmic reticulum, either directly or by small transport vesicles. This allows the proteins made in the rough endoplasmic reticulum to enter the Golgi apparatus. The cisternae of the *trans* face are connected to the cell membrane by large, secretory vesicles that contain proteins to be secreted outside the cell. The membranes of the *cis* face more closely resemble the membranes of the endoplasmic reticulum, while the membranes of the *trans* face more closely resemble the cell membrane.

Secretory cells have a well-developed Golgi apparatus, but in other cells, the Golgi apparatus is small.

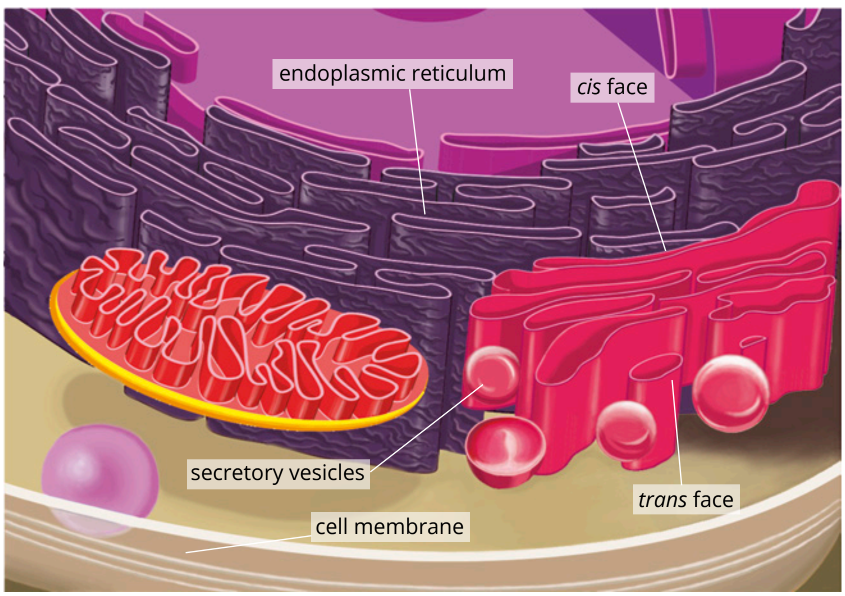


FIGURE 2.2.9 The Golgi apparatus has a *cis* face, which faces the endoplasmic reticulum, and a *trans* face, which faces the cell membrane.

Lysosomes

Lysosomes are the cell's recycling units—specialised vesicles that digest unwanted matter (Figure 2.2.11). They are found in animal cells, and lysosome-like structures have been found in some plant cells. Lysosomes are formed when a transport vesicle containing enzymes is released from the Golgi apparatus, and fuses with another vesicle called an **endosome**. The endosome contains molecules brought into the cell by the process of **endocytosis**.

Lysosomes fuse with vesicles containing unwanted matter, such as damaged organelles or foreign matter. The enzymes in the lysosome then digest the unwanted matter. Small molecules that the cell can reuse may diffuse back into the cytoplasm. The rest are either retained in the lysosome, or released from the cell by the process of **exocytosis**.

BIOFILE CCT

Camillo Golgi (1844–1926)

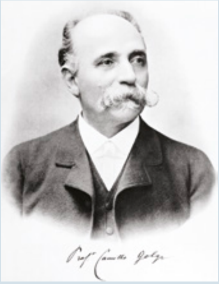


FIGURE 2.2.10 Camillo Golgi

Camillo Golgi was an Italian physician, anatomist and histologist (Figure 2.2.10). Golgi developed a method of staining tissues with silver nitrate, which he called the 'black reaction'. He was the first person to describe the membranous structure in the cell that is now known as the Golgi apparatus or Golgi complex.

Golgi won the Nobel Prize in Physiology and Medicine in 1906, but it was for his work on the structure of the nervous system, not his discovery of the Golgi apparatus. In fact, many biologists at the time did not think the Golgi apparatus existed—it was only in the 1950s that its existence was finally confirmed by electron microscopy. Today, scientists are increasingly referring to the Golgi apparatus as simply 'the Golgi'.

FIGURE 2.2.11 Two lysosomes in a pancreatic cell (SEM). Lysosomes (green) are small, spherical vesicles bound by a single membrane (clearest on lower lysosome). Partially digested material can be seen in each lysosome.

Exocytosis is the process by which cells move products through the cytoplasm to the cell membrane. Products are packaged into vesicles, which fuse with the cell membrane, expelling their contents outside the cell.

Endocytosis is the opposite of exocytosis. A curved pit forms in the cell membrane, and takes on a circular shape. It then pinches off into a vesicle that makes its way into the cell, and the cell membrane reforms into its original shape.

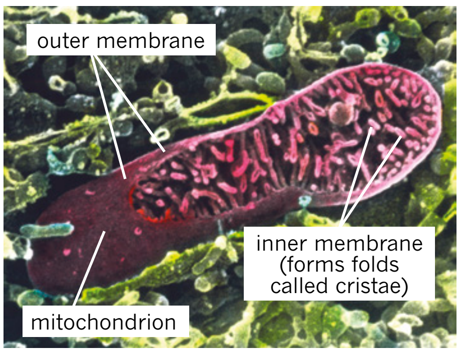


FIGURE 2.2.13 A single mitochondrion in the cytoplasm of an intestinal epithelial cell (SEM). The cylindrical mitochondrion (pink, centre) has a highly folded internal membrane, which provides a large surface area for cellular respiration.

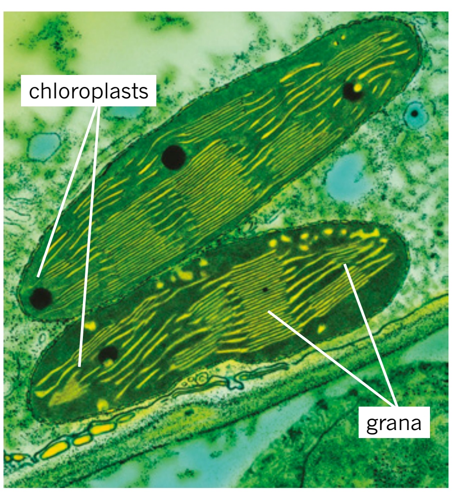


FIGURE 2.2.14 Two chloroplasts in the leaf of a pea plant (*Pisum sativum*). Each chloroplast has been cut lengthways and is surrounded by an external double membrane. The chloroplasts contain chlorophyll and stacks of flattened membranes (yellow) called grana. This image was produced using a transmission electron microscope (TEM).

Summary: Synthesis and processing of proteins and lipids

Protein and lipid synthesis and processing are shown in Figure 2.2.12. DNA is transcribed inside the nucleus into mRNA, which moves out of the nucleus and binds to ribosomes. Ribosomes synthesise proteins using the information on the mRNA. Proteins that will be secreted out of the cell are made in the ribosomes bound to the rough endoplasmic reticulum. These proteins are modified and packaged in the Golgi apparatus. Vesicles arising from the Golgi apparatus can fuse with the cell membrane, releasing their contents from the cell, or can insert membrane-bound proteins into the cell membrane. Lipids are synthesised and processed in the smooth endoplasmic reticulum.

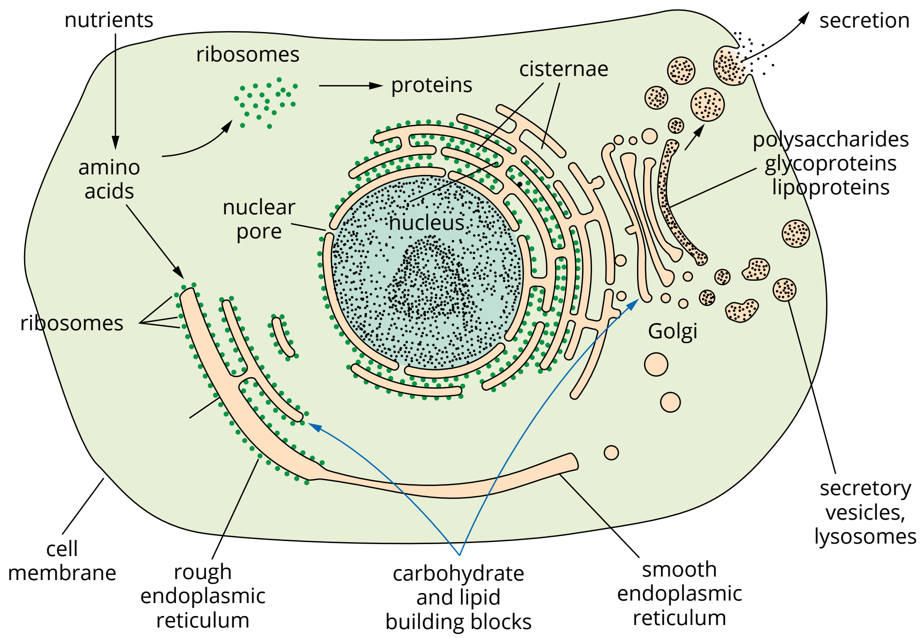


FIGURE 2.2.12 This typical animal cell shows the organelles involved in synthesising and processing proteins and lipids.

Energy transformations

Mitochondria and chloroplasts are the organelles involved in energy transformations within eukaryotic cells.

Mitochondria

Mitochondria are organelles composed of two membranes. The inner membrane of the mitochondria has folds called cristae (Figure 2.2.13). There are two different compartments inside mitochondria: an intermembrane space and the matrix. The matrix is the fluid-filled space enclosed by the inner membrane and contains a double-stranded DNA molecule. Different enzymes are found inside each compartment and on each membrane.

Mitochondria play an important role in cellular respiration, converting the chemical energy in organic molecules (from food) into energy that cells can use. The inner mitochondrial membranes are the site of the chemical reactions of cellular respiration. The highly folded structure of the inner membranes increases the surface area over which these chemical reactions can take place.

The number of mitochondria in a cell is related to the cell's energy requirements. Very active cells, such as heart muscle cells, have many thousands of mitochondria.

Chloroplasts

Chloroplasts are organelles involved in photosynthesis. They contain large amounts of a green pigment called chlorophyll (Figure 2.2.14). Like mitochondria, chloroplasts also possess a double-stranded DNA molecule. Chloroplasts are present in plants and many protists, but never in animals or fungi.

Chloroplasts are composed of a system of three membranes: the outer membrane, the inner membrane and the thylakoid system. Thylakoids are disc-shaped sacs that form compartments within the chloroplast. Different compartments contain different enzymes.

Chloroplasts trap light energy, which is used to split water molecules into hydrogen and oxygen in the process of photosynthesis. The hydrogen then combines with carbon dioxide to make glucose, and the oxygen is released into the atmosphere as a waste product.

+ ADDITIONAL

The endosymbiotic theory

Endosymbiosis is a type of **symbiosis** in which one organism lives inside the other. The endosymbiotic theory suggests that it is possible for a large cell to ingest a smaller bacterial cell, and for the two to become dependent on each other. In 1910, Constantin Mereschkowsky first suggested that endosymbiosis was the origin of large, complex cells. But he was ridiculed for his idea, and it was largely forgotten.

In 1967, American biologist Lynn Margulis (Figure 2.2.15) published a paper titled 'On the origin of mitosing cells'. In this paper, she argued that mitochondria and chloroplasts were both once free-living prokaryotic cells that came to live inside larger cells. Eventually, the mitochondria and chloroplasts became specialised organelles that cannot survive outside the cell today.

FIGURE 2.2.15 Lynn Margulis, shown here earlier in her career

Although most biologists were extremely sceptical when Margulis first put forward her hypothesis, it is now widely accepted. Evidence supporting the theory includes the fact that mitochondria and chloroplasts have double membranes and their own DNA, which you would expect if they were once free-living prokaryotes (Figure 2.2.16).

Scientists now think that mitochondria came from aerobic bacteria (bacteria that can survive in the presence of oxygen), and that chloroplasts came from cyanobacteria (bacteria that obtain their energy by photosynthesis).

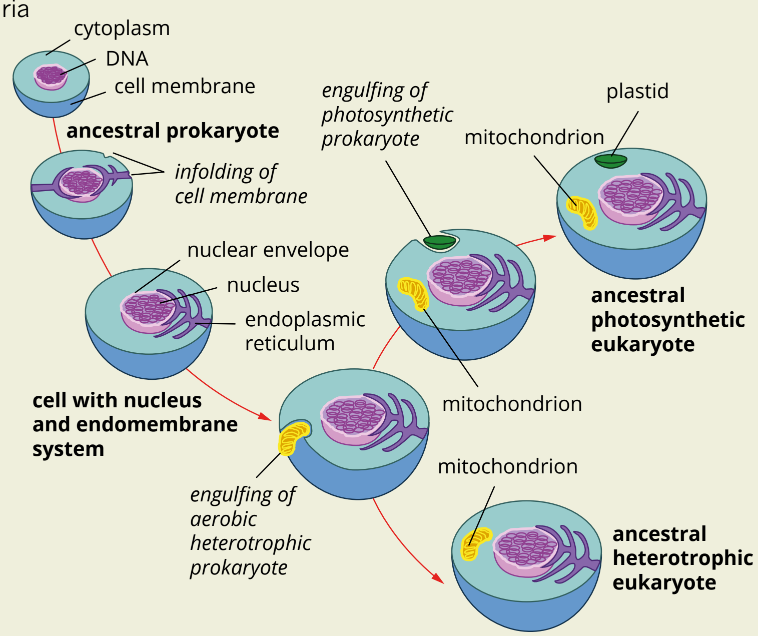


FIGURE 2.2.16 The theory of endosymbiosis explains how eukaryotes originated from the symbiosis of prokaryotic ancestors.

Storage and cell structure

The organelles involved in storage and supporting the cell structure in eukaryotic cells are vacuoles, plastids, the cell wall, the cytoskeleton, centrioles, cilia and flagella.

Vacuoles

A vacuole is a membrane-bound, liquid-filled space that stores enzymes and other organic and inorganic molecules. Vacuoles occur in most cells, but the number varies. They also differ between animal cells and plant cells (Figure 2.2.17). Animal cells contain many small, temporary vacuoles, but most plant cells contain a single, large, permanent vacuole surrounded by a membrane called the **tonoplast**. Plant vacuoles provide structural support by helping to maintain turgor. They also function in a similar way to the lysosomes found in animal cells.

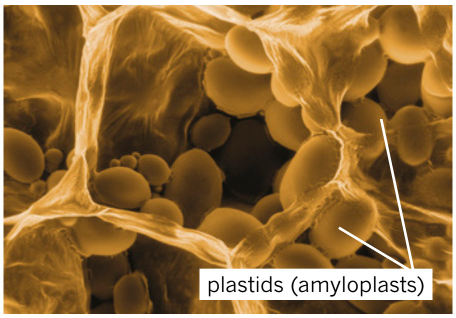


FIGURE 2.2.18 Amyloplasts (oval) in the sectioned cells of a potato (*Solanum tuberosum*) (SEM). Amyloplasts are a type of plastid that store starch.

FIGURE 2.2.17 A section through a plant cell, revealing its internal structure (SEM). At the centre of the cell is a large vacuole, which maintains the cell's shape, stores useful materials and digests waste products.

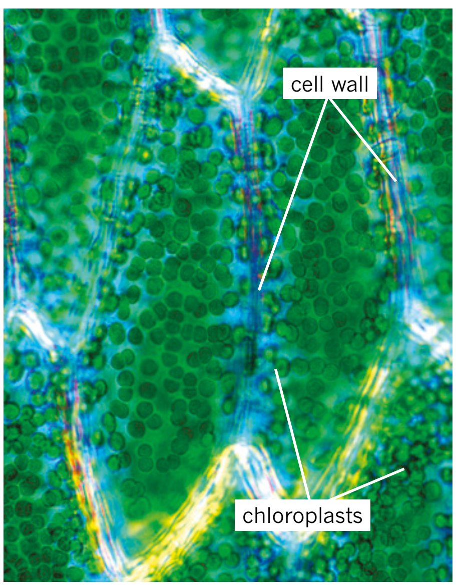


FIGURE 2.2.19 Cells in a leaf of shining Hookeria moss (*Hookeria lucens*) (LM). The leaf is made up of a single layer of cells. A cell wall (blue) encloses each cell, and many chloroplasts (round, green) containing the pigment chlorophyll are seen in each cell.

Plastids

Plastids are organelles involved in the synthesis and storage of different chemical compounds. They contain a double-stranded DNA molecule and are surrounded by a double membrane. Plastids develop from simple organelles called proplastids. Animal cells do not contain plastids. Plastids can be:

- chloroplasts, which are involved in photosynthesis and are found only in plants and some protists
- leucoplasts, which are involved in storage
  - amyloplasts are a type of leucoplast found in plants (Figure 2.2.18)
  - they are commonly responsible for synthesising and storing starch, but can also convert the starch back to sugar when the plant requires energy
- chromoplasts, which contain colour pigments and occur in petals and fruit.

Cell wall

The cell wall is a rigid structure that surrounds the cell membrane of plant cells, fungal cells and some prokaryote cells (Figure 2.2.19). In plants, the cell wall is composed mainly of cellulose. Fungal cell walls are made of chitin.

The cell wall provides support, prevents expansion of the cell, and allows water and dissolved substances to pass freely through it. Lignin in the cell walls of woody plants, especially in the **xylem**, gives them additional strength.

Xylem is the tissue in vascular plants that transports water and nutrients upwards from the roots.

Cytoskeleton

The cytoskeleton consists of microtubules of a protein called tubulin, and filaments of a protein called actin (Figure 2.2.20). The cytoskeleton supports the cell's structure, allows the cell to move, and helps transport organelles and vesicles within the cell.

Centrioles

Centrioles are a pair of small, cylindrical structures composed of microtubules (Figure 2.2.21). They are present in most eukaryotic cells, but many plant cells do not have them. Centrioles are involved in cell division and the formation of cell structures such as cilia and flagella.

Cilia and flagella

Cilia and flagella (singular cilium and flagellum) are hair-like structures on the surface of cells (Figures 2.2.22 and 2.2.23). They consist of an arrangement of microtubules that are enclosed by an extension of the cell membrane. Both structures are involved in the movement of the cell or things around the cell. Cilia move with an oar-like motion, and are usually shorter and more numerous than flagella.

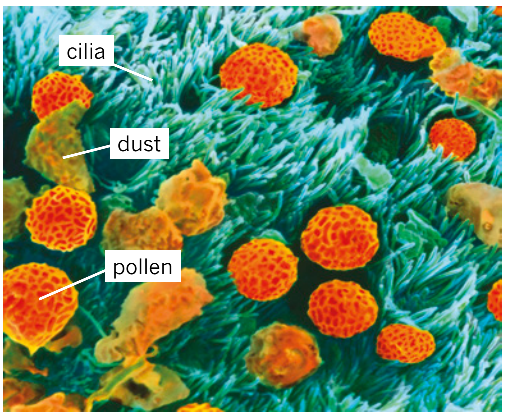


FIGURE 2.2.22 The surface of the trachea (windpipe) showing pollen (orange) and dust (brown) that has been inhaled (SEM). The surface cells have hair-like cilia (green), which together with mucus, trap airborne particles and remove foreign matter from the airways and lungs.

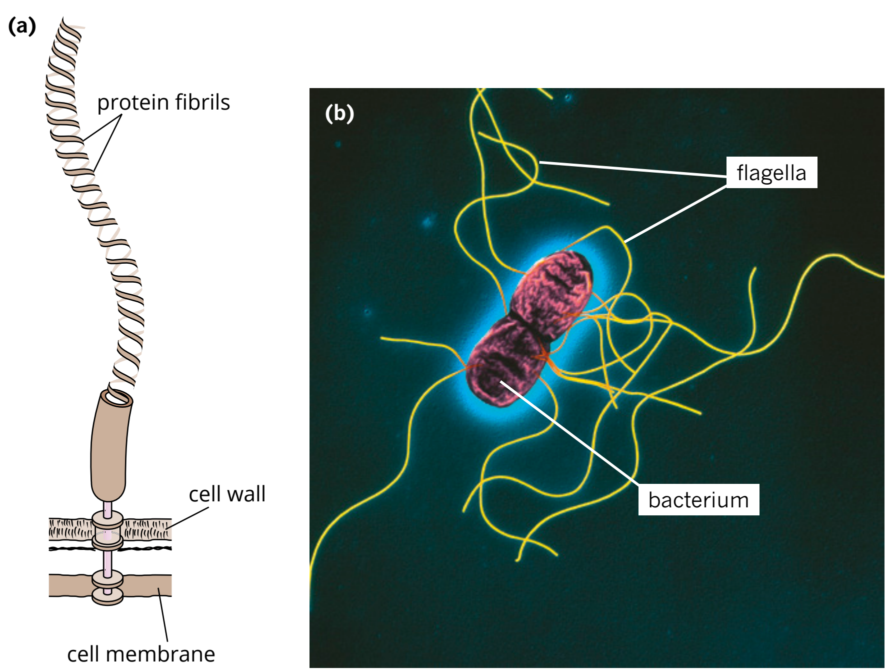


FIGURE 2.2.23 (a) Bacterial flagella consist of three protein fibrils coiled in a helical pattern. (b) An SEM of a *Salmonella typhimurium* bacterium. This rod-shaped, gram-negative bacterium moves using its long, hair-like flagella (yellow).

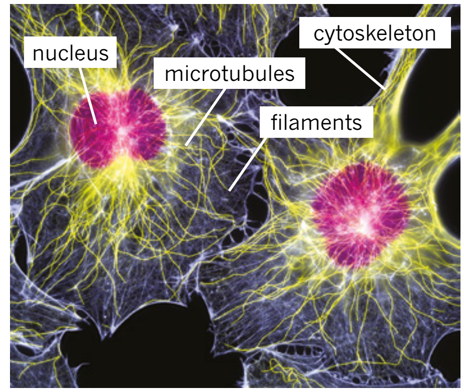


FIGURE 2.2.20 Two fibroblast cells, showing their nuclei (purple) and cytoskeleton. This image was produced using fluorescence light microscopy.

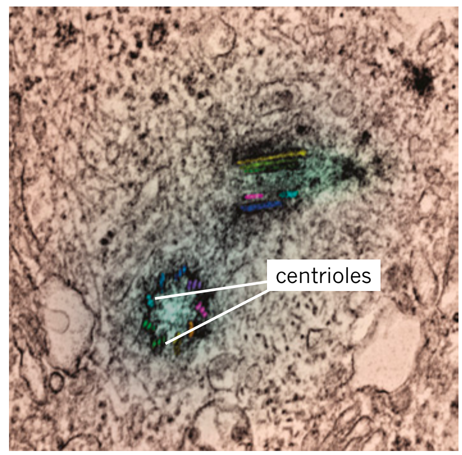


FIGURE 2.2.21 Centrioles are the organelles that help a cell divide into two. These cylindrical structures are mainly composed of the protein tubulin. Centrioles are involved in assembling the spindle that pulls cells apart during mitosis.

PA 1.1 PA 1.1 WS 1.3

SKILLBUILDER N

Drawing scaled diagrams of cells

Cells are so small that they are measured in micrometres, and can usually only be observed using a microscope. It is important to learn how to draw and label diagrams of equipment and biological specimens in your studies of biology. There are certain rules you must follow when producing diagrams for your reports and exams.

When drawing scientific equipment, diagrams should:

- be large, simple, two-dimensional pencil drawings
- have ruled lines where possible
- keep proportions realistic.

Below are some guidelines for drawing biological specimens.

- Draw the whole diagram (including labels, lines, magnification, heading and scale) in pencil.
- Do not draw the diagram in a circle representing the field of view.
- Draw your diagram with simple, clear lines (do not sketch).
- Do not shade your drawing.
- Make your diagram as large as possible (at least 10 × 10 cm).
- Do not draw structures that cannot be seen.
- Include clear labels for the features you want to highlight (Figure 2.2.24).
- Place labels outside the drawing (Figure 2.2.24).
- Make sure label pointers do not cross over each other.
- Labels should line up on either side of the diagram.
- Do not use arrowheads on lines pointing to features.
- Include a scale bar or scale (e.g. 1: 100) in the diagram, or state the magnification (e.g. ×400) in the caption.

If there are lots of features to show, a supporting diagram is useful. This is where you show the general structures in a photo and pair it with a diagram showing cellular detail.

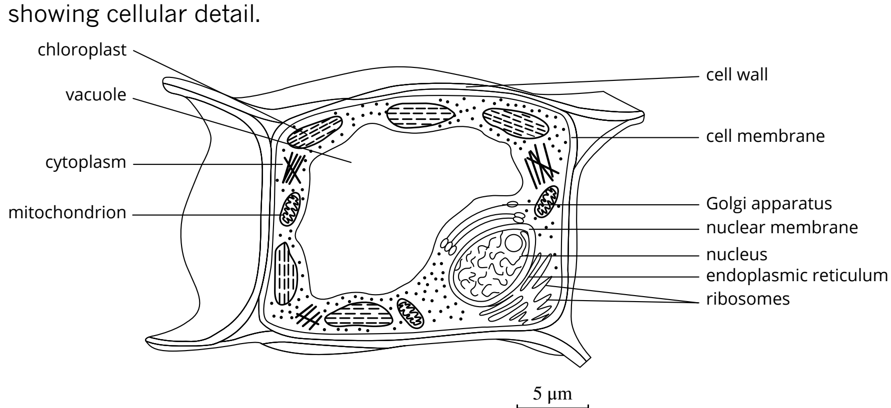


FIGURE 2.2.24 This scaled diagram of a typical plant cell has clear labels for each type of organelle. Magnification: x1000

2.2 Review

SUMMARY

- Eukaryotic cell structures are organised into membrane-bound compartments (organelles). This is called cell compartmentalisation.
- Compartmentalisation in eukaryotic cells increases the efficiency of cellular processes by allowing:
  - enzymes and reactants to be close together in high concentrations and in the right conditions
  - incompatible chemical reactions to occur simultaneously within the cell.
- Compartmentalisation also protects organelles from changes in the external environment.
- The main structures in eukaryotic cells that are involved in the synthesis and processing of proteins and lipids are the nucleus, ribosomes, rough and smooth endoplasmic reticulum, the Golgi apparatus and lysosomes.
- The main structures in eukaryotic cells that are involved in energy transformations are mitochondria and chloroplasts (plant and protist cells only).
- The main structures in eukaryotic cells that are involved in storage and cell structure are vacuoles, plastids, the cell wall (plant and fungi cells only), the cytoskeleton, centrioles, cilia and flagella.
- Plant and protist cells contain chloroplasts for photosynthesis, but animal and fungi cells lack these structures.
- Plant and fungi cells are surrounded by cell walls but animal and most protist cells do not have a cell wall.

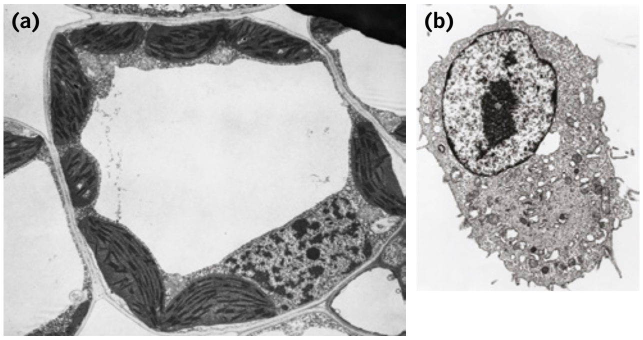
KEY QUESTIONS

1 What function is shared by mitochondria and chloroplasts?

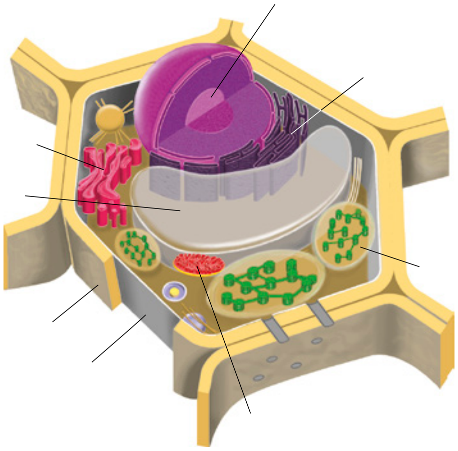
2 Which one of the following options lists only membrane-bound organelles?

A nuclei, mitochondria, vacuoles, ribosomes
B nuclei, mitochondria, centrioles, ribosomes
C nuclei, mitochondria, vacuoles, chloroplasts
D nuclei, mitochondria, vacuoles, cell walls

3 Which of the images in the following figure is a plant cell? Explain your answer.



4 Label the parts of the plant cell in the following diagram.



5 List the main differences between plant and animal cells.

2.3 Cell membranes

The cell membrane encloses the contents of a cell and controls the movement of substances between the **extracellular fluid** outside the cell and the **intracellular fluid** (or cytosol) inside the cell (Figure 2.3.1). The cell membrane therefore helps maintain an environment within the cell that differs from the **external environment**. As well as controlling the transport of molecules into and out of the cell, the cell membrane is also involved in cell recognition and communication with other cells. In this section, you will learn about the composition and characteristics of the cell membrane, described using the **fluid mosaic model** of the cell membrane.

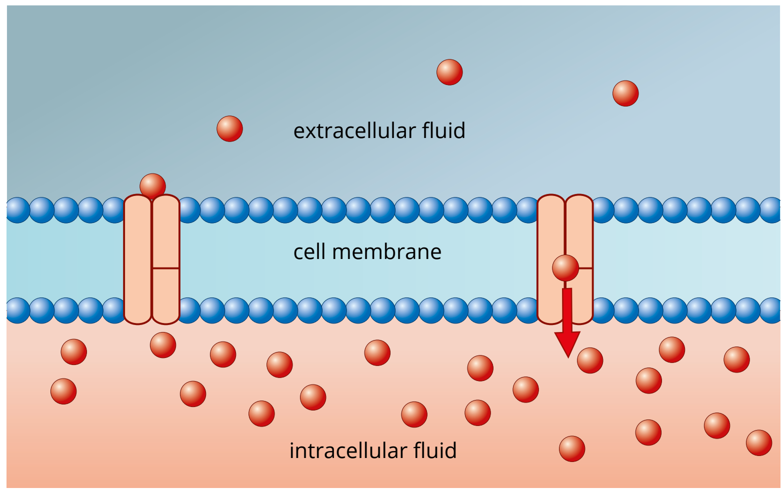


FIGURE 2.3.1 The cell membrane regulates the movement of substances between the extracellular fluid and intracellular fluid.

EXTRACELLULAR FLUID IN UNICELLULAR ORGANISMS

Cells exist in a watery environment of extracellular fluid. This can be a large amount of fluid, or just a thin surface layer. The composition of the extracellular fluid is critical to cell stability and function, because it provides them with the nutrients they need to survive.

For unicellular organisms, the extracellular fluid is simply the watery, external environment in which they live. Unicellular organisms can do little to control their environment, and may die if it changes significantly. However, some unicellular organisms, such as yeasts, can become dormant until environment conditions are favourable. Other unicellular organisms can move slowly to a place where the conditions suit their needs. For example, unicellular algae can move towards light, and some bacteria can detect chemicals, and then move towards nutrients or away from toxic substances.

Extracellular fluid is the body fluid outside cell membranes. It includes blood plasma and interstitial fluid (fluid that surrounds and bathes the cells).

FIGURE 2.3.2 Crabs have an external skeleton (carapace) that protects them from water loss when on land.

EXTRACELLULAR FLUID IN MULTICELLULAR ORGANISMS

The cells of multicellular organisms are more protected from the external environment than the cells of unicellular organisms. Multicellular organisms have more control over the environment in which their cells exist, and are therefore less affected by changes in the external environment. Whether they live in water or on land, multicellular organisms have an outer layer that acts as a protective barrier (Figure 2.3.2). This outer layer creates an **internal environment** for the organism that differs from their external environment. In multicellular organisms, the environment of the cells is the extracellular fluid that surrounds them.

Most multicellular organisms can regulate the conditions of their internal environment very precisely. This allows multicellular organisms to provide the specific conditions needed by specialised cells and tissues. It also allows their cells to function more efficiently. Commonly regulated aspects of the internal environment are:

- temperature
- oxygen concentration
- carbon dioxide concentration
- pH (acidity or alkalinity)
- osmotic pressure (concentrations of salts or ions)
- nitrogenous waste concentration
- glucose concentration.

The way cells interact with the extracellular fluid of the internal environment is regulated by the cell membrane.

> The intracellular environment inside all living cells is a layer of fluid that is in contact with an outer cell membrane.

CELL MEMBRANE COMPOSITION: THE FLUID MOSAIC MODEL

The fluid mosaic model describes the structure of the cell membrane. The model was first proposed by Jonathan Singer and Garth Nicholson in 1972, and is now widely accepted as the basic model of all biological membranes. According to this model, cell membranes consist of a **bilayer** (two layers) of phospholipid molecules. Other molecules, such as proteins, carbohydrates and **cholesterol**, are scattered throughout the bilayer (Figure 2.3.3).

The fluid mosaic model is a representation of our current knowledge of the cell membrane. It is modified and updated as developments in cellular techniques and technology allow more information to be gathered.

> Cell membranes are phospholipid bilayers (two layers of molecules) that enclose the cytoplasm and subdivide the cell into compartments (organelles).

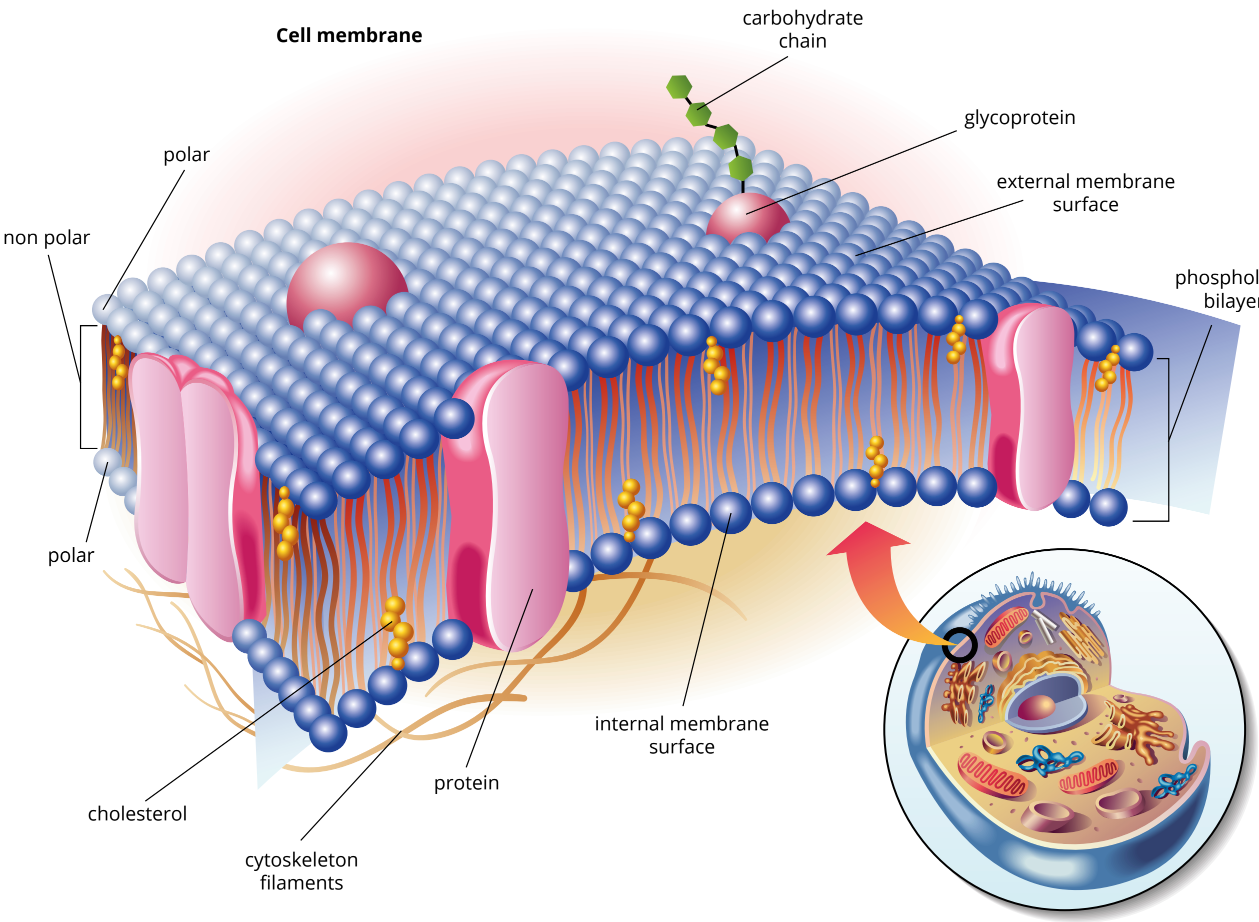


FIGURE 2.3.3 This fluid mosaic model of a cell membrane shows the phospholipid bilayer in which large protein molecules are embedded.

Cell membranes have the same basic structure in all organisms. The structure serves to separate the interior of the cell (the cytoplasm) from its external environment. Most membranes are also asymmetrical, meaning one layer has different properties from the other. For example, the pattern of proteins and carbohydrate molecules in the external surface is different from the pattern in its internal surface.

The composition and characteristics of the cell membrane are related to the cell's needs and function. The cell membrane performs many functions, such as transporting molecules into and out of the cell, cell recognition and communication with other cells (Figure 2.3.4).

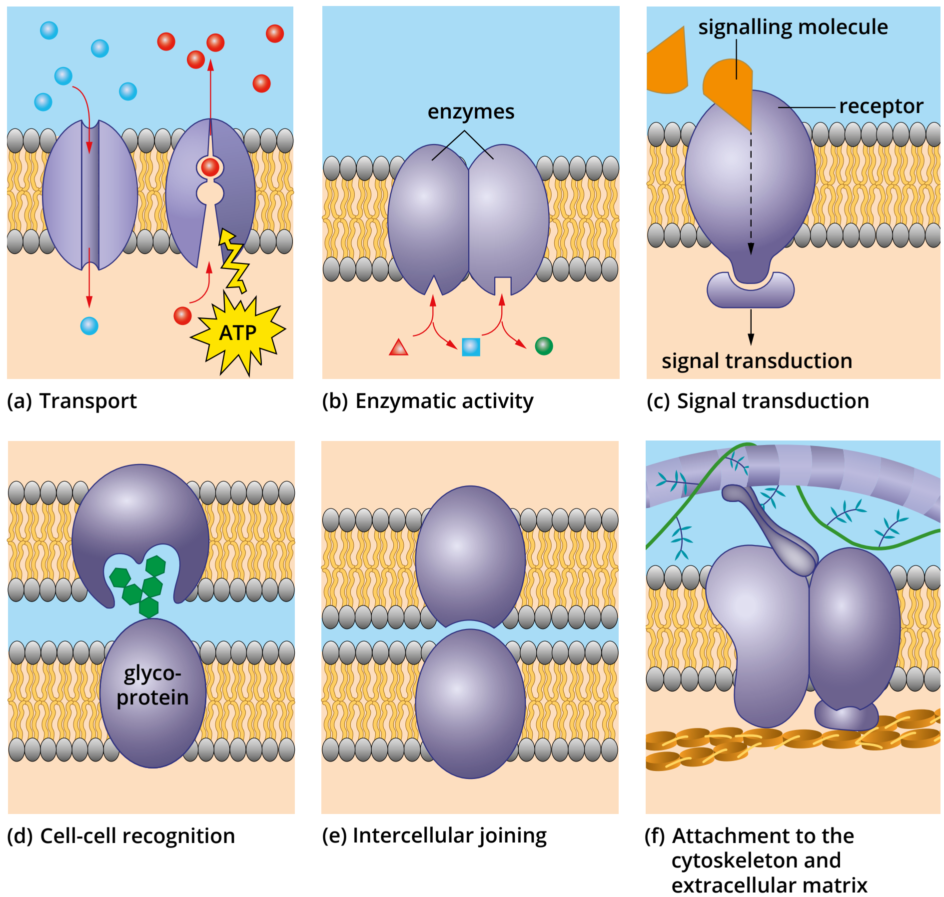


FIGURE 2.3.4 Cell membrane proteins have many different functions.

Phospholipids

Phospholipid molecules have a hydrophilic (water-attracting) 'head' and two hydrophobic (water-repelling) 'tails' (Figure 2.3.5). The phospholipid bilayer of the cell membrane is called a bilayer because it has two layers of phospholipids. The hydrophilic heads form the outside and inside lining of the cell membrane, and the hydrophobic tails of the two layers of phospholipids meet in the middle. The hydrophilic head of a phospholipid is made up of a phosphate group and glycerol, while the two hydrophobic tails are made up of fatty acids. The tails can be made of saturated fatty acids or unsaturated fatty acids.

Because phospholipids have a hydrophilic head and two hydrophobic tails, they react to the presence of water (Figure 2.3.6). If the phospholipids are in contact with water on one side and oil on the other side, all the hydrophilic heads will be embedded in water and the tails will be embedded in the oil. However, if the phospholipids are in contact with water on both sides, all the hydrophilic heads will be embedded in water, and the hydrophobic tails will point towards each other, with oil sandwiched in between. This bilayer arrangement shelters the hydrophobic tails of the phospholipids from water, while exposing the hydrophilic heads to water.

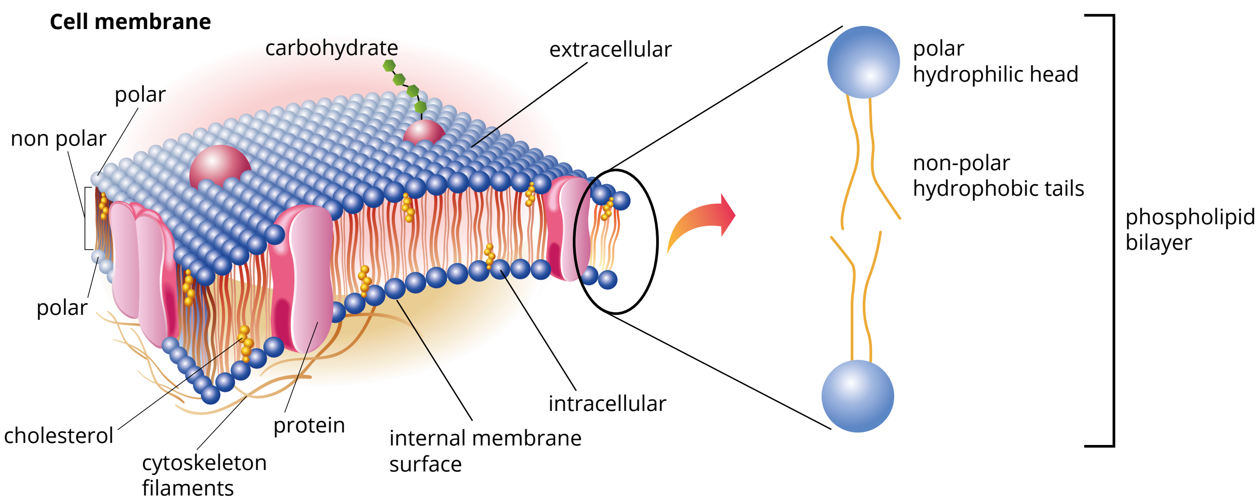


FIGURE 2.3.5 Each phospholipid molecule in the cell membrane has a hydrophobic 'tail' and a hydrophilic 'head'.

> **i** A phospholipid molecule consists of long-chain fatty acids (which are hydrophobic) and a phosphate (which is hydrophilic). It is the major component of cell membranes.

The phospholipid nature of cell membranes makes them impermeable to water-soluble particles, ions and polar molecules. The movement of these molecules across the membrane is controlled by protein channels. The protein channels allow the cell to regulate the exchange of molecules with the exterior environment. This regulation is central to important processes that keep the cell alive, such as cell respiration, digestion and waste elimination. You will learn more about the movement of materials across cell membranes in Section 3.1.

Cell membranes are fluid structures. This means that individual phospholipid molecules (and some proteins) are free to move about within the layers. However, they rarely cross from one side of the cell membrane to the other. The level of membrane fluidity depends on the percentage of unsaturated fatty acids in the phospholipid molecules—the greater the percentage, the more fluid the membrane.

Fluidity of the cell membrane

The molecules of the cell membrane are not fixed in place. Most of the phospholipids and some of the proteins can move about laterally, while some molecules can occasionally flip-flop transversely across the membrane (Figure 2.3.7). The rate at which the molecules move within a layer of the cell membrane varies. Proteins in the membrane can move sideways, but at a much slower rate than the phospholipids. The ability of the phospholipids and proteins to move gives the cell membrane its fluid nature.

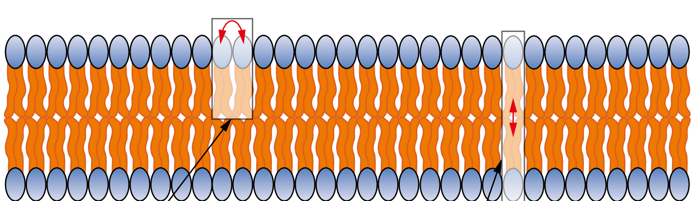


FIGURE 2.3.7 Phospholipids can move about in cell membranes.

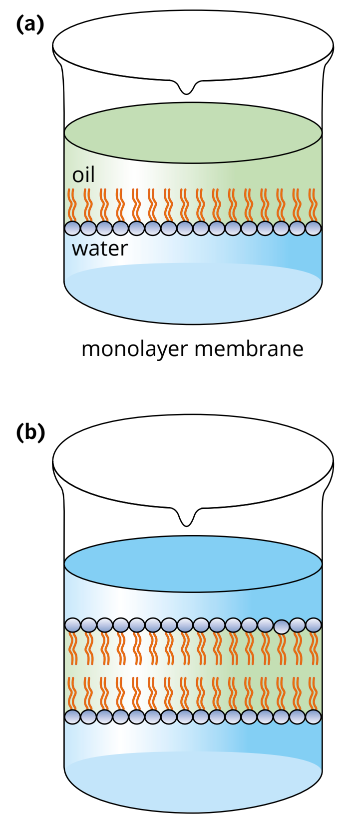


FIGURE 2.3.6 (a) Arrangement of phospholipids in the presence of water on one side and oil on the other side, and (b) arrangement of phospholipids in the presence of water on both sides, forming a bilayer

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The fluidity of the cell membrane is very important. It affects the permeability of the membrane to substances, and the capacity for proteins to move within the membrane to particular areas where they are required to carry out their function.

Factors that alter the fluidity of the cell membrane include:

- phospholipid composition and structure
- temperature
- the presence of cholesterol.

Temperature

As the temperature increases, the fluidity of cell membranes increases. This is because the phospholipids become less closely packed together and are able to move more freely.

As the temperature decreases, a cell membrane with a large proportion of saturated fatty acids may solidify at a certain point. This will not occur in a cell membrane with a large proportion of unsaturated fatty acids, because the kinks in the tails of these fatty acids prevent the phospholipids from becoming too closely packed.

Cholesterol

Membranes contain many fatty molecules, including cholesterol molecules, between the phospholipid molecules (Figure 2.3.8). The cholesterol found in eukaryotic cell membranes gives stability to the cell membrane without affecting its fluidity. It also reduces the permeability of the cell membrane to small, water-soluble molecules.

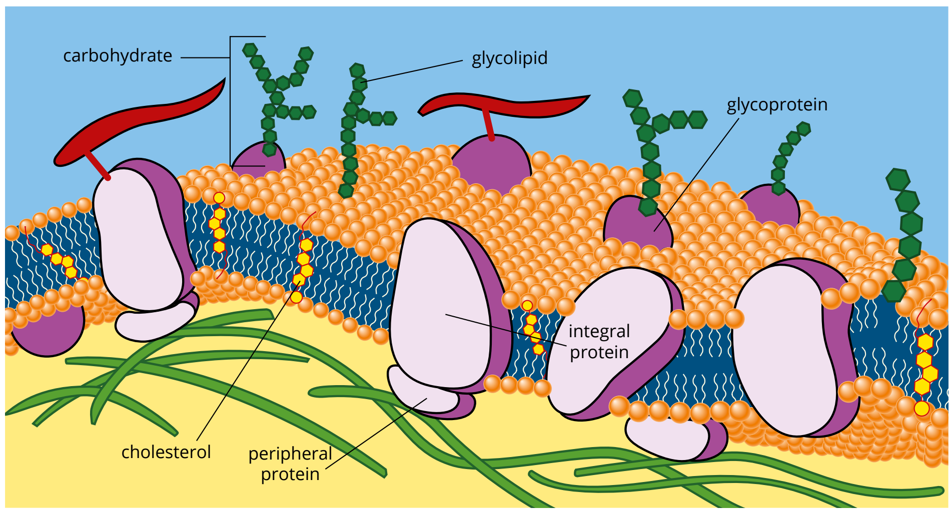


FIGURE 2.3.8 Components of the cell membrane

Proteins

Like phospholipid molecules, proteins in the cell membrane can move about to some extent. However, this movement may be limited to particular regions of the cell membrane.

Proteins that are a permanent part of the cell membrane are called **integral proteins**. Proteins that are a temporary part of the cell membrane are called **peripheral proteins**. Peripheral proteins bind to integral proteins, or penetrate into one surface of the cell membrane (Figure 2.3.8). When integral proteins span both phospholipid layers, they are also called **transmembrane proteins**. Transmembrane proteins are involved in several important cellular and intercellular activities (Figure 2.3.4).

Carbohydrates

WS 1.4

Carbohydrates associated with cell membranes are usually linked to protruding proteins (forming **glycoproteins**) or to lipids (forming **glycolipids**) on the outer surface of the membrane (Figure 2.3.8). Carbohydrates play a role in recognition and adhesion between cells, and in the recognition of antibodies, hormones and viruses by cells.

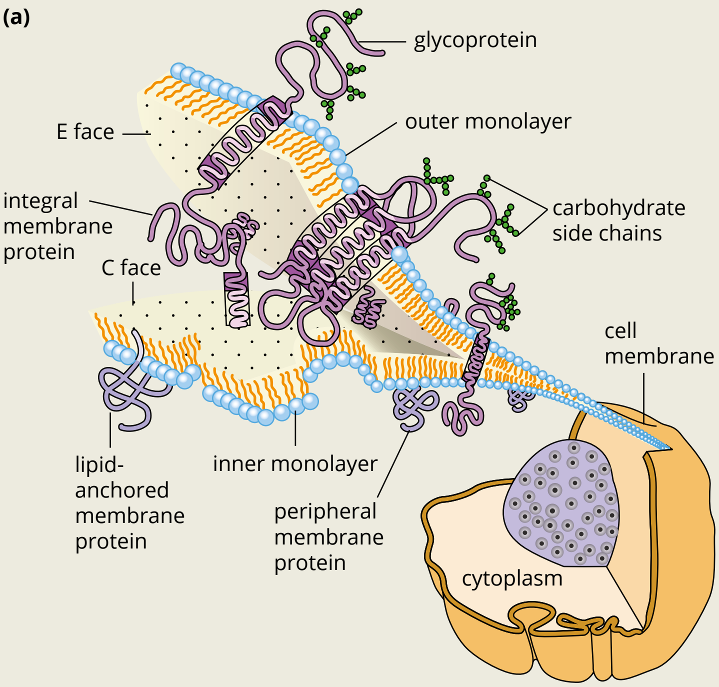
BIOLOGY IN ACTION ICT

Freeze-fracture electron microscopy

Freeze-fracture electron microscopy is a technique that can be used to demonstrate that proteins are embedded in the cell membrane. Using this method, the cell membrane can be split into its two phospholipid layers to reveal the structure of the cell membrane's interior (Figure 2.3.9a).

The first step in freeze-fracture electron microscopy is to prepare the cell. A cell is frozen and then fractured with a knife. The plane of the fracture often follows the hydrophobic tails of the phospholipid bilayer, splitting it into two monolayers—an outer or E (extracellular) surface, and an inner or C (cytoplasmic) surface (Figure 2.3.9b). Membrane proteins are not 'broken' by the technique, and so are found on only one of the two layers.

Once the cell membrane has been split into the two layers, a scanning electron microscope is used to take a picture of each layer. Membrane proteins are shown as 'bumps', demonstrating that proteins are embedded in the phospholipid bilayer.



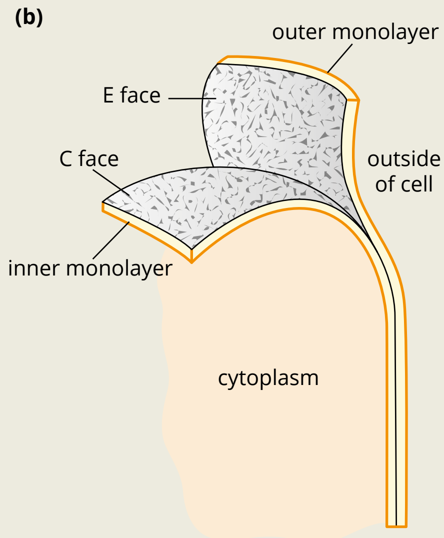


FIGURE 2.3.9 (a) The fracture plane has passed through the hydrophobic interior of the membrane, revealing the inner surfaces of the two monolayers. Integral membrane proteins remain embedded in one of the layers. (b) Surface view of the monolayers. The bumps on the surfaces are transmembrane proteins.

2.3 Review

SUMMARY

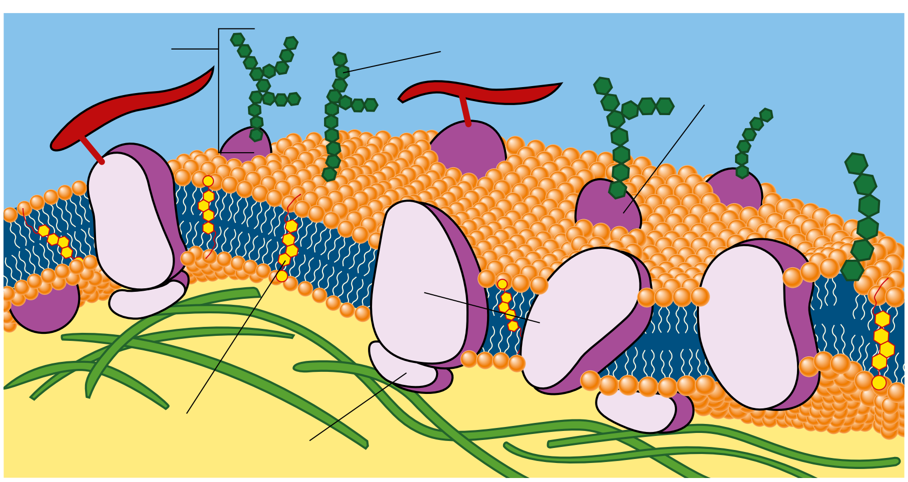
- The external environment of living cells is the layer of extracellular fluid that is in direct contact with the cell membrane.
- Cell membranes separate the interior of the cell (the cytoplasm) from the external environment, and control the movement of substances between the two.
- The fluid mosaic model describes the fluid structure of the cell membrane.
- For unicellular organisms, the extracellular fluid is the watery environment in which they live and that they can do little to control.
- Multicellular organisms have an internal environment that is more or less independent from the external environment. The external environment of the cells is therefore the extracellular fluid that surrounds them.
- Most multicellular organisms can regulate aspects of their internal environment, including concentrations of salts (ions), temperature, pH (acidity or alkalinity), and concentrations of nutrients, water and wastes.
- Cell membranes consist of a double layer of phospholipid molecules. They contain protein molecules of various sizes, as well as fatty molecules, such as cholesterol. They are also associated with other molecules, including carbohydrates.
- The phospholipid nature of the cell membrane makes it impermeable to water-soluble particles, ions and polar molecules.
- The cell membrane is semipermeable. This means some materials can move across it while others can't.
- Cell membrane proteins:
  - provide selective channels that enable water-soluble particles and ions to travel through the cell membrane (transport)
  - catalyse reactions associated with the cell membrane (enzymatic activity)
  - communicate with the external environment and other cells (signalling and cell-to-cell recognition)
  - bind with other cells (intercellular joining).
- Cells exchange nutrients and waste with their environment across the cell membrane through channel proteins. Membrane-bound enzymes catalyse reactions. The rate of exchange is related to the volume of the cell and its metabolic needs or function, such as the transport or absorption of substances.

KEY QUESTIONS

1 List three functions of the cell membrane.

2 Membrane-bound proteins may have carbohydrates attached. What are these proteins, and what is their function?

3 Label the key components of the cell membrane shown in the following diagram.



4 With reference to a cell, where is the extracellular fluid found?

5 **a** What is the main structural component of a cell membrane, and what other molecules are associated with it?

b What role do (i) proteins and (ii) cholesterol play in the functioning of the membrane?

2.4 Investigating cells

Cytology is the study of cells. Cytologists use a variety of tools and techniques to study cells, including several microscopy techniques. Modern microscopy techniques, including light and electron microscopy, have greatly advanced our understanding of the structure and function of cells.

CELL SIZE

Cells vary greatly in size (Figure 2.4.1). Most cells are only visible under a **light microscope**, and their size is usually measured in micrometres (μm) (note: 1000 μm = 1 mm). Although most cells are microscopic, there are some exceptions. For example, the egg cell of some bird species can be many centimetres in diameter.

Some typical cell lengths are:

- bacterium: 0.1–1.5 μm
- human cell: 8–60 μm
- plant cell: 10–100 μm
- paramecium (a single-celled eukaryote): about 150 μm.

The thickness of cell membranes also differs between cells, and can be between 0.004 and 0.1 μm thick.

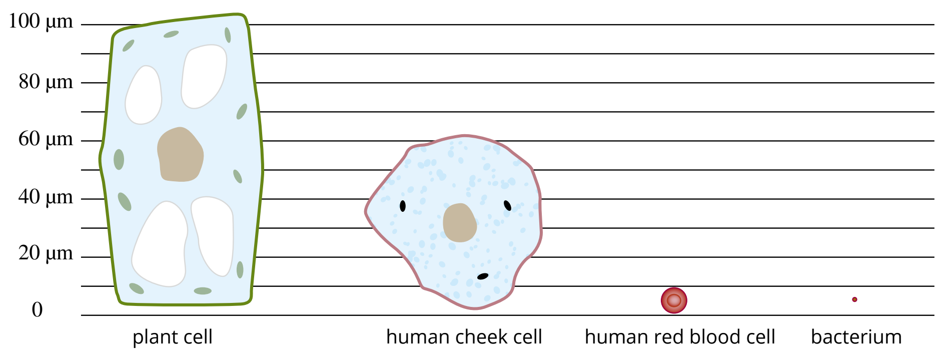


FIGURE 2.4.1 A typical plant cell compared with a human cheek cell, human red blood cell and a bacterium. Note that eukaryotic cells are much larger than most prokaryotic cells.

SKILLBUILDER N

Estimating cell size

A light microscope has two lenses: the eyepiece (or ocular lens) and the objective lens. Both lenses magnify the specimen. To calculate the total magnification, multiply the magnification of the ocular lens by the magnification of the objective lens. Ocular lenses usually have a magnification of ×10.

Total magnification = ocular lens magnification × objective lens magnification

When looking down a microscope, the size of a cell can be estimated by working out the diameter of the field of view.

The field of view is the area that you can see when you look down a microscope. The typical magnifications and field of view in school microscopes are listed in Table 2.4.1.

TABLE 2.4.1 Light microscope magnifications and field of view

Ocular lens (eyepiece) magnification	Objective lens magnification	Total magnification (ocular lens × objective lens)	Field of view diameter
×10	×4	×40	4.5 mm
×10	×10	×100	1.5 mm
×10	×40	×400	450 μm
×10	×100	×1000	150 μm

To work out the size of a cell, you divide the number of cells you can see in the field of view by the diameter of the field of view.

$$\frac{\text{field of view (mm)}}{\text{number of cells}} = \text{length of each cell (mm)}$$

For example, if you are viewing a cell at ×100 magnification and it fills the field of view, it is about 1.5 mm across. If you are viewing a cell at ×100 magnification and two cells span the field of view, each cell is about 1.5 mm ÷ 2 = 0.75 mm across.

Microscopes often have a ruler or mini-grid to measure the objects being viewed. If the microscope you are using doesn't have a ruler or mini-grid, use a transparent ruler to measure the field of view at each magnification and accurately estimate cell size.

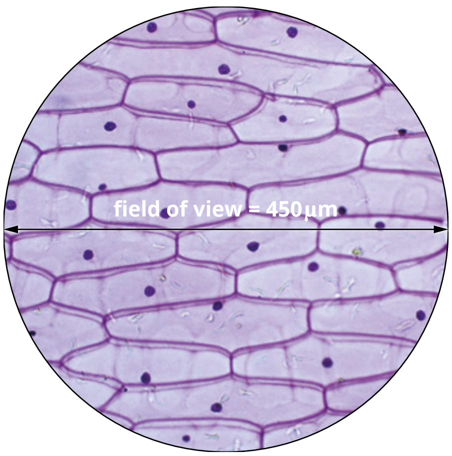


FIGURE 2.4.2 The field of view when looking down a microscope at ×400 magnification is about 450 µm.

Worked example 2.4.1 N

CALCULATING CELL SIZE

You set up a microscope with an ocular lens magnification of ×10 and an objective lens magnification of ×40. Looking down the microscope you see the field of view in Figure 2.4.2.

a Calculate the total magnification and identify the diameter of the field of view.	
Thinking	**Working**
Identify the ocular lens magnification.	Ocular lens magnification = ×10
Identify the objective lens magnification.	Objective lens magnification = ×40
Calculate the total magnification = ocular lens magnification × objective lens magnification.	Total magnification = 10 × 40 = ×400
Identify the diameter of the field of view.	450 µm (refer to table in the Estimating cell size SkillBuilder on pages 97–98)

b Calculate the length of the cells.	
Thinking	**Working**
Identify how many cells span the field of view.	3
Calculate the length of each cell: $\frac{\text{field of view } (\mu m)}{\text{number of cells}} = \text{length of each cell } (\mu m)$	$\frac{450\,\mu m}{3\text{ cells}}$ = 150 µm (length of each cell)

Worked example: Try yourself 2.4.1

CALCULATING CELL SIZE

You set up a microscope with an ocular lens magnification of ×10 and an objective lens magnification of ×10. Looking down the microscope you count 11 cells across the field of view.

a Calculate the total magnification and identify the diameter of the field of view.

b Calculate the length of the cells.

BIOFILE ICT

Development of the microscope

The microscope has made many important scientific discoveries possible. The first microscope was created in the late 16th century when Dutch lens grinders, Hans and Zacharias Janssen, placed two lenses in a tube.

In 1675, Anton van Leeuwenhoek crafted a simple microscope made of a single lens and a flat piece of metal (Figure 2.4.3). With this microscope, Leeuwenhoek achieved a magnification of up to ×200. Leeuwenhoek was the first to observe single-celled organisms, which he called 'animalcules', meaning 'tiny animals'.

As lens-grinding techniques advanced, microscopes became more powerful and had better resolution. Today, scanning tunnelling microscopes can produce three-dimensional images of items at the atomic level.

FIGURE 2.4.3 Leeuwenhoek's microscope was one of the earliest, created in the 1670s. It consisted of a single lens mounted on a flat piece of metal. Using his handcrafted microscopes, Leeuwenhoek was the first to observe and describe single-celled organisms.

LIGHT MICROSCOPY

Most cells are so small that they can only be seen with a microscope. The **light** microscope uses light and a system of lenses to magnify the image. One lens is called the objective lens, and the other is the eyepiece or ocular lens. The total magnification of a microscope is calculated by multiplying the magnifying power of the **ocular lens** (eyepiece) by the magnifying power of the **objective lens**. For example, an ocular lens with a magnifying power of 4 times (×4) used with an objective lens with a magnifying power of 10 times (×10) gives a total magnification of 40 times (×40).

One of the main advantages of light microscopy is that it can be used to view living cells in colour.

Preparation time is usually quick and simple, and coloured stains can highlight different components of cells. To view cells through a light microscope, the cells first need to be prepared and mounted on a glass slide. Different techniques for preparing and mounting cells are used for different specimen types. Some common **specimen** preparation techniques are:

- **whole mounts**, which involve placing the whole organism or structure directly on the slide, and are used for thin structures or very small organisms such as *Daphnia* (Figure 2.4.4)
- **smears**, which are used for cells suspended in fluid (e.g. blood), or cells that have been scraped from a surface, such as cervical cells collected during a Pap smear (Figure 2.4.5)
- **sections**, which are very thin slices of specimens prepared by embedding the specimen in paraffin wax, and using a slicing instrument called a microtome to cut sections of just one layer of cells (3–7 μm) (e.g. liver tissue) (Figure 2.4.6).

FIGURE 2.4.4 Light micrograph (LM) of *Daphnia magna* whole mount specimen. *Daphnia* are small freshwater crustaceans about 1.5–5 mm long. This image shows the compound eye (black), the digestive system containing algae (green), and developing eggs (white, round cells to the left). *Daphnia* reproduce asexually. Magnification: ×21

FIGURE 2.4.6 Sections of rat liver tissue prepared for viewing through a light microscope. Specimens have been embedded in paraffin wax, thinly sliced, mounted on a slide and stained.

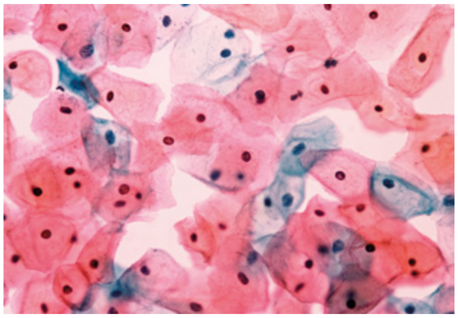


FIGURE 2.4.5 Light micrograph (LM) of normal human cervical cells collected from a Pap smear. The cytoplasm is stained pink or blue, and the small nuclei are the dark dots at the centre of the cells. Magnification: ×400

After preparing, mounting and staining a specimen, the glass slide is placed on the stage of the microscope, under the lenses. Light travels through the specimen and into the lens system. The image is then viewed by eye or with a digital camera.

The condenser lens beneath the movable stage is used to concentrate light from the light source onto the specimen, and the image is focused using the coarse and fine adjusters. Different parts of the specimen can be viewed by moving the specimen on the stage.

Light microscopy techniques used in cytology include histology, autoradiography, fluorescence and confocal microscopy. Each of these uses visible light to examine cells and tissues.

SKILLBUILDER CCT

Using a microscope

1 Set up the microscope on a level bench that is low enough for you to look comfortably through the eyepiece (ocular lens).

2 Turn the revolving nosepiece so that the lowest-power (shortest) objective lens, the scanning lens (usually ×4) is in position.

3 To see through a microscope, you need a source of light. The light could be reflected from a mirror, or there could be a built-in lamp. It is useful to be able to adjust the amount of light. Some microscopes have a disc with holes of different sizes, while others have a diaphragm. Adjust the amount of light coming through by:

- enlarging or reducing the size of the hole in the diaphragm
  - this can be done by moving a lever on the side
  - big holes allow more light and allow you to see a brighter image
- adjusting the mirror or lamp
  - if your microscope has a mirror, do not let sunlight fall onto it; bright light can damage your eyes.

4 Look at the stage. The object you are viewing must be placed over the hole in the stage so that light can pass through it.

5 Clips, called stage clips, may be present to hold the microscope slide in place. (Not all microscopes have stage clips.)

6 Lower the objective lens using the coarse-focus knob. It should be close to, but not touching, the specimen. You will need to look from the side to make sure. Take note of which way you are turning the knob to wind the lens down. Be sure to lower the stage so the lens does not collide with it when turning the revolving nosepiece.

7 Look through the eyepiece and raise the objective lens. You will need to wind the coarse-focus knob the opposite way. When you are close to focus, refine using the fine-focus knob, if available. If you have a microscope with a moving stage, then turn the coarse-focus knob so the stage moves downward or away from the objective lens. What you see is called the field of view.

8 If you miss the focus, repeat steps 6 and 7.

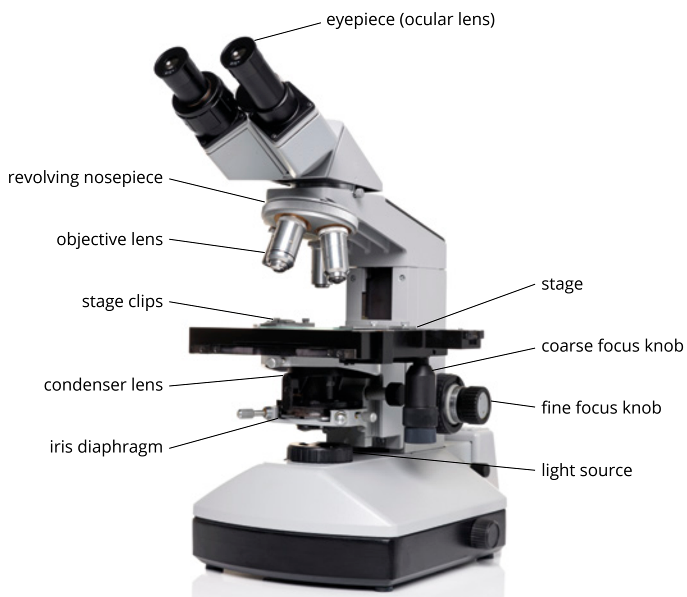


FIGURE 2.4.7 A light microscope and its parts

Fluorescence microscopy

A **fluorescence microscope** is used to examine cells, cellular structures or any fluorescing material, such as stains, dyes or antibodies, with fluorescent molecules. Fluorescent cells contain molecules that absorb light at a particular wavelength (called the exciting wavelength) and emit light at another wavelength. Filters are used to block out the exciting wavelength, allowing the light emitted by the fluorescing molecules to be seen against a black background (Figure 2.4.8). If the cells do not contain fluorescent molecules, fluorescent dyes (called markers) can be added that attach to different cellular structures, such as DNA or cell wall components (Figure 2.4.8). Fluorescence techniques allow scientists to visualise structures and materials inside cells that are usually too small to view. They can also target and detect particular proteins, and diagnose disease.

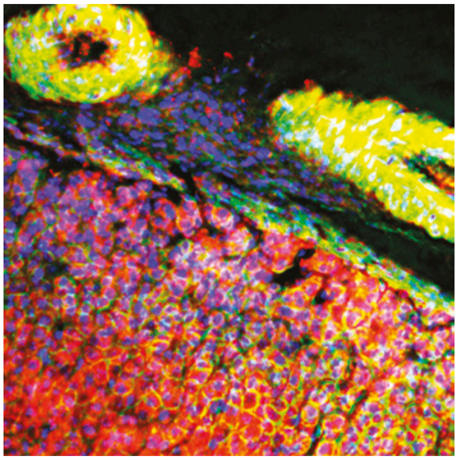


FIGURE 2.4.8 A fluorescence LM of a stained section through an adrenal gland. Enzymes are red, cell nuclei are blue, and the smooth muscle of blood vessels is green and yellow.

Confocal microscopy

A **confocal microscope** allows scientists to obtain 'optical sections' of a cell or tissue, stained with fluorescent markers, without actually sectioning or slicing the cells.

Confocal microscopy can obtain high-resolution (high-quality) images of very thin sections of a specimen (Figure 2.4.9). It involves passing laser light through a pinhole and lens, which provides highly focused light onto only a tiny part of the specimen. This eliminates light reflecting from adjacent parts of the section, which normally blur the image. Slowly scanning the object in this way, together with a suitable computer, allows you to view an 'optical section' of the sample.

Thicker samples can be imaged in thin sections and then reconstructed in three dimensions using image analysis software. At present, confocal microscopes and the computer software required are very expensive, and the images take a long time to make. However, confocal microscopes can produce remarkable three-dimensional views of living structures.

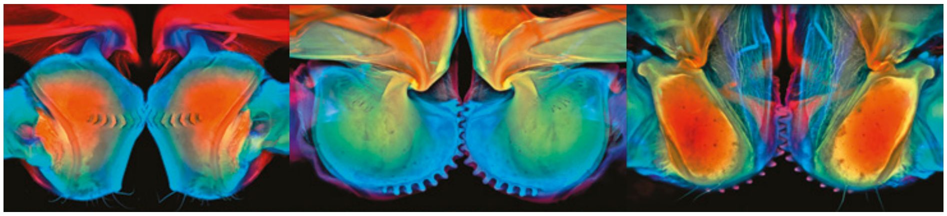
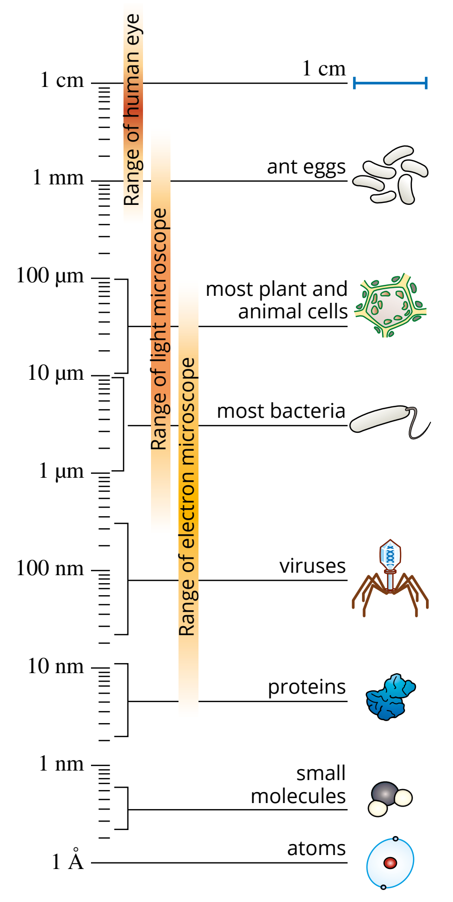


FIGURE 2.4.9 A confocal laser scanning micrograph of an insect called the green cone-headed planthopper (*Acanalonia conica*). The image (left to right: posterior, dorsal and ventral views) shows cog or gear-like structures at the top of each hind leg, which allow the hind legs to interlock and move together in perfect synchrony. Laser light from the microscope causes the stained specimen to fluoresce and reveal variations in the chitin (the main component in the exoskeleton).

ELECTRON MICROSCOPY

An **electron microscope** uses an electron beam rather than light to view objects. This allows us to see structures in far more detail than is possible using light microscopy (Figure 2.4.10). An electron microscope produces a narrow beam of electrons. The beam is maintained by electromagnetic lenses, which are coils that surround the tube and emit an electromagnetic field. Electrons striking the specimen are either absorbed, scattered, or pass through it.

The image obtained with an electron microscope has a much higher resolution and a greater depth of field than an image from a light microscope. In microscopy, the depth of field is the range of depth that a specimen is in acceptable focus; e.g. if a microscope has a shallow depth of field, it will be difficult to focus clearly on a thick specimen. Electron microscopy produces only black and white images, but these are often coloured later to highlight important features.



$1 \text{ cm} = 10 \text{ mm} = 10^4 \text{ µm} = 10^7 \text{ nm} = 10^8 \text{ Å}$

FIGURE 2.4.10 A comparison of the ranges of the light and electron microscopes. Note that the scale is logarithmic.

Transmission electron microscopy

In **transmission electron microscopy** (TEM) the electron beam travels through an ultrathin section (less than 100 nm thick) of a specimen. This allows very fine details of cellular structures to be seen (Figure 2.4.11).

Because the specimen must be in a vacuum in the TEM, it is first chemically fixed to stop the structures from collapsing, and then dehydrated with alcohol. It is then embedded in a plastic resin, sectioned with a diamond cutter called an ultramicrotome, and stained.

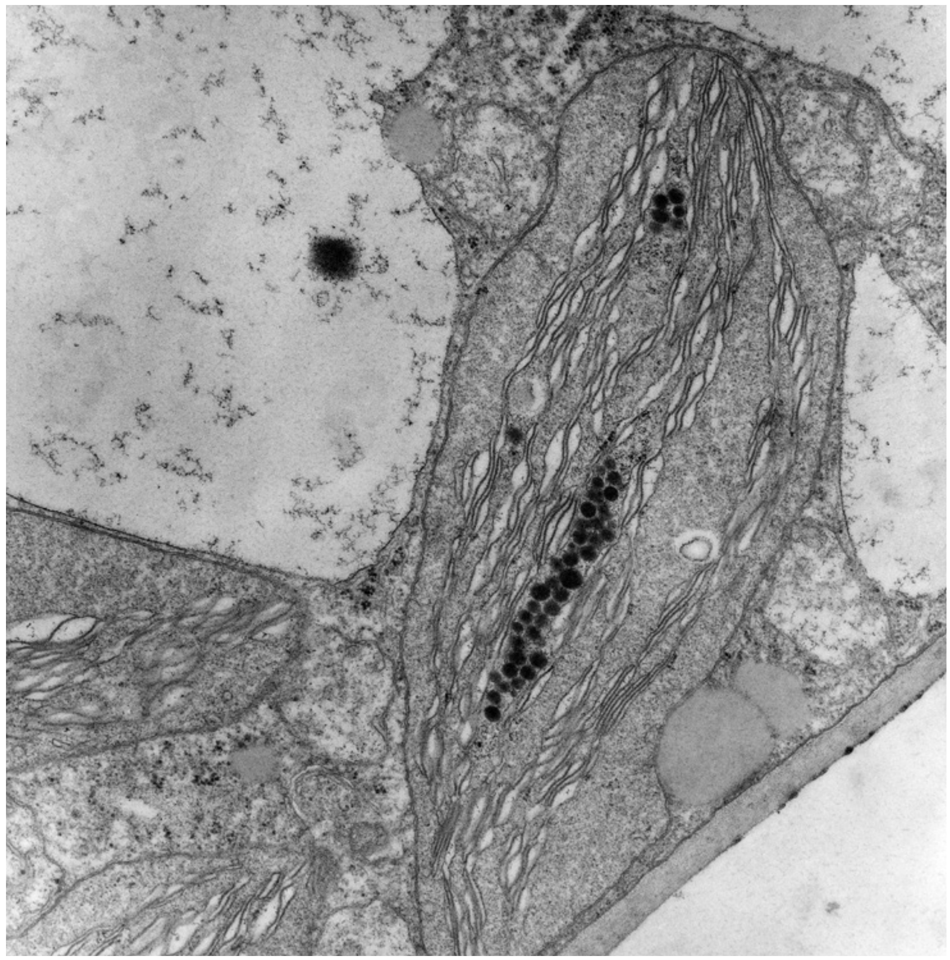


FIGURE 2.4.11 A TEM image of a plant leaf showing chloroplasts, with lipid droplets visible in one chloroplast. The pale area to the upper left is a vacuole. The cell wall is visible at the lower right.

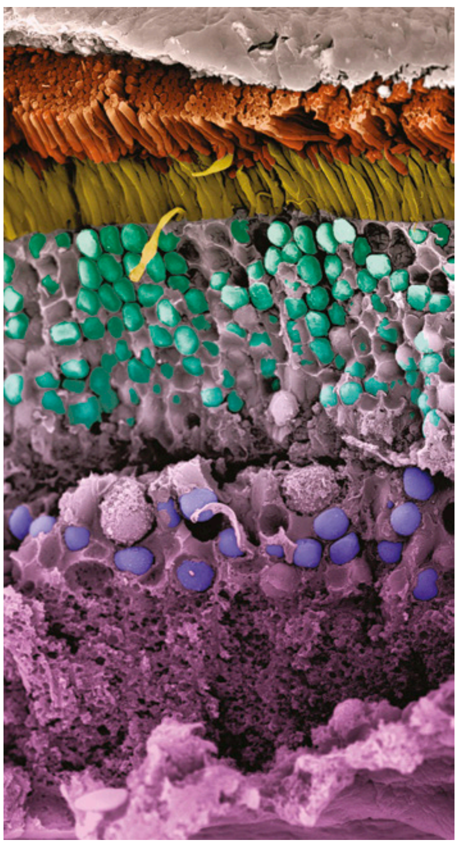


FIGURE 2.4.12 A coloured SEM image of a section through the retina of an eye

Scanning electron microscopy

In **scanning electron microscopy** (SEM) the electrons are bounced off a specimen that has been coated with an extremely thin layer of gold. This gives a high-resolution picture of the surface features, but cannot show internal details (Figure 2.4.12).

SKILLBUILDER N

Calculating percentages

Scientists use percentages to express a ratio or fraction of a quantity.

To express one quantity as a percentage of another, use the second quantity to represent 100%.

For example, expressing 6 as a percentage of 24 is like saying '6 is to 24 as x is to 100':

$$\frac{6}{24} = \frac{x}{100}$$

$$x = \frac{6}{24} \times 100$$

$$= 25\%$$

To calculate a percentage of a quantity, the percentage is expressed as a decimal, and then multiplied by the quantity.

For example, to calculate 40% of 20:

$$x = \frac{40}{100} \times 20$$

$$= 0.4 \times 20$$

$$= 8$$

AUTORADIOGRAPHY

Autoradiography is a method that allows scientists to identify specific organelles or the location of molecules within a cell or tissue. In autoradiography, the tissue is first treated with a radioactively labelled substance. The substance is taken up into the part of the cell that is being investigated (Figure 2.4.13). The tissue is then sliced into very thin sections, which are then placed against a very thin, high-resolution photographic film. The radioactive substance emits beta particles, which produce an image on the film. The tissue sections are then stained to locate the cellular structures seen in the photographic image. This technique can be used to reveal the activity levels of organelles in different situations.

Although autoradiography is still sometimes used with light microscopy, it is more commonly used today with electron microscopy.

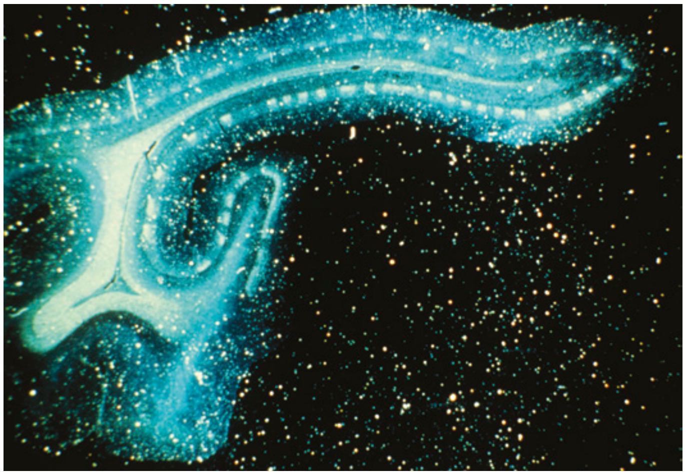


FIGURE 2.4.13 An autoradiograph of a slice through nerve tissue from the visual centre of the brain. It shows how the brain receives visual messages from one eye. The active areas of the brain have absorbed a radioactive chemical, causing them to glow.

BIOLOGY IN ACTION ICT

The synchrotron and its use in biology

A synchrotron is a large machine called a particle accelerator. Inside a synchrotron, powerful magnets are used to guide a beam of electrons into a particular path, usually a circle. The electrons whiz around the circle, accelerating to almost the speed of light. This technology allows scientists to view structures at the atomic scale, and has many applications in science and engineering.

The first synchrotron was built in 1945 and was the size of a small room. Today, the largest synchrotron—the Large Hadron Collider, in Switzerland—has a circumference of 27 km. The Australian Synchrotron in Melbourne (Figure 2.4.14) is one of the most advanced synchrotrons in the world. It can produce an extremely intense beam of radiation in a wide range of wavelengths. Most biological investigations using synchrotrons involve the visible wavelengths of light.

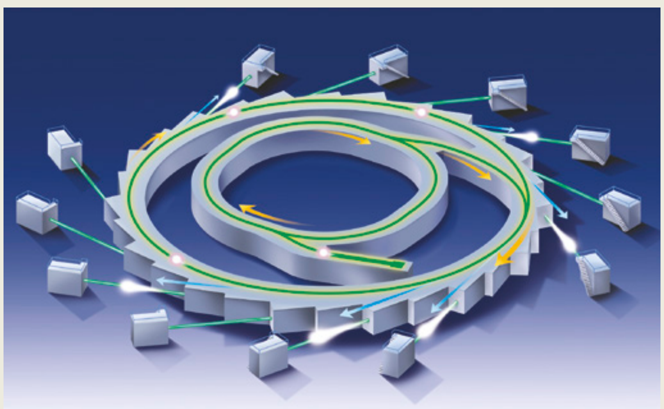


FIGURE 2.4.14 The Australian Synchrotron is almost the size of the Sydney Cricket Ground. The large diameter is needed to accelerate particles to almost the speed of light. Light of different wavelengths can be obtained from several points around the circumference of the synchrotron, indicated by the small boxes around the outside of the ring.

The special nature of synchrotron light

The visible light wavelengths are just a small part of the electromagnetic wavelengths that a synchrotron can generate. Visible light lies between the longer wavelengths (radio waves, microwaves and infrared) and the shorter wavelengths of ultraviolet light, X-rays and gamma rays (Figure 2.4.15).

Synchrotron light allows us to see matter at the atomic scale, such as the nanosecond-by-nanosecond behaviour of protein molecules (e.g. antibodies). The technology enables scientists to collect data on the structure of proteins in a few hours—data that would once have taken weeks or months to obtain.

A synchrotron allows complex protein structures to be determined quickly and is central to drug design and development. It allows further development of medical imaging technologies and the analysis of biological samples to potentially help diagnose diseases. While structural biology is the most important synchrotron application, they are useful in many other areas, such as nanotechnology and materials science.

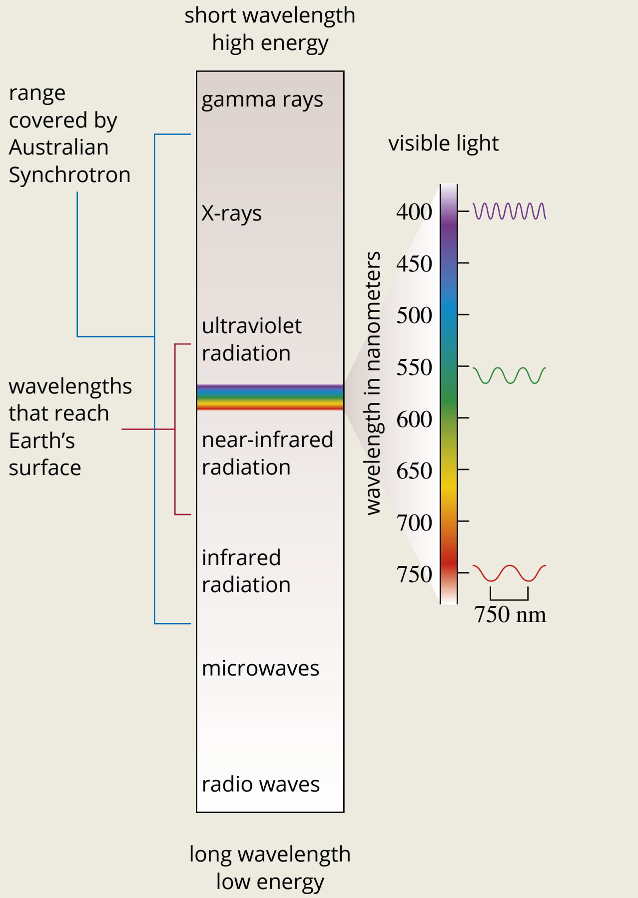


FIGURE 2.4.15 The electromagnetic spectrum, showing the range generated by the Australian Synchrotron and the range of visible light

+ ADDITIONAL

Cell theory

Spontaneous generation and biogenesis

Until the 1850s, scientists generally accepted an idea known as the 'theory of spontaneous generation' to explain the origin of living things. This theory states that life can be formed from non-living things—even from a grain of sand.

Experiments by Francesco Redi in the 1600s, Lazzaro Spallanzani in the 1700s and Louis Pasteur in the 1800s showed that this so-called spontaneous generation was actually contamination by microorganisms. These important experiments—along with significant discoveries made by other scientists—showed that living things cannot be generated by non-living things, and laid the foundation for the cell theory.

Cell theory was formally developed in 1839 by Matthias Jakob Schleiden and Theodor Schwann, with contributions from Rudolf Virchow. The theory rejects spontaneous generation and supports the idea of 'biogenesis': that living things only come from other living things.

Cell theory states that:

- all organisms are composed of cells
- all cells come from pre-existing cells
- the cell is the smallest living organisational unit.

History of cell theory

Hooke: the discovery of cells

The first description of cells was made by Robert Hooke, an English natural philosopher. Hooke made a thin slice of cork from the bark of a tree and examined it under a microscope he had made himself (Figure 2.4.16). He saw that the bark was made up of hundreds of little 'empty boxes' that gave it a honeycomb appearance. He called the boxes 'cells'. In 1665, he published his discoveries in a book called *Micrographia*.

Hooke later realised he had been looking at empty dead cells. When he looked at fresh plant tissue, he noted the cells appeared to contain water. A few years later, Marcello Malpighi produced more detailed descriptions of plant cells.

Leeuwenhoek: first observations of living cells

In 1676, Anton van Leeuwenhoek, from the Netherlands, observed many living cells under the microscope, including bacteria, blood cells and sperm. He was the first to describe the reproduction of unicellular organisms, which he called 'animalcules'.

FIGURE 2.4.16 Robert Hooke's drawing of his light microscope in *Micrographia*, published in 1665

Francesco Redi: evidence for biogenesis

In the 1660s, Francesco Redi's experiments rejected the theory of spontaneous generation and supported the theory of biogenesis. Redi placed meat in three jars: the first was sealed, the second had netting covering the opening, and the third was left open. He observed maggots on the meat in the open jar, but no maggots on the meat in the sealed jar or the jar covered with netting. Although the meat in the netting-covered jar was exposed to the air, flies couldn't get into the jar, and so no maggots appeared. Redi's observations showed that life could not spontaneously generate and must come from other living things (biogenesis).

Lazzaro Spallanzani: rejection of spontaneous generation

Lazzaro Spallanzani's experiments in the 1670s also rejected the theory of spontaneous generation. Spallanzani put broth in four flasks: the first was open, the second was sealed, the third was boiled and then left open, and the fourth was boiled and then sealed. He found microbes growing in all flasks except the fourth, which had been boiled and sealed. Spallanzani concluded that the microbes came from outside the flask and that boiling the broth killed them. His experiments rejected the theory that life could arise from non-living matter.

Lamarck and Dutrochet: all living things are composed of cells

By the early 1800s, the microscope had become a standard tool of biologists, and living animal and plant cells were easy to observe. French scientist Jean Lamarck stated that all living things are a mass of cells, and that complex solutions move in and out of cells. Another French scientist, René Dutrochet, supported this idea, stating: “Plants are composed entirely of cells, or of organs that are obviously derived from cells…the same is true for animals”.

Schleiden and Schwann: cell theory

By the mid 1800s, the fundamental principle that entire organisms are composed of highly organised groups of cells was broadly accepted. This was largely because of the work of two German scientists: Matthias Jakob Schleiden on plant tissues, and Theodor Schwann on animal tissues. In 1839, Schleiden and Schwann formulated cell theory.

Remak and Virchow: the theory of biogenesis

Until the 1850s, most biologists still believed that cells formed spontaneously from body fluids or from the nucleus, which they thought was the embryo of a new cell. Robert Remak, a scientist from Germany, was the first to discover that new cells were formed by a single cell dividing in two, with the nucleus dividing at the same time (Figure 2.4.17). In the 1850s, German scientist Rudolph Virchow used Remak’s discovery to popularise the theory of biogenesis: that all cells come from pre-existing cells. Because of Virchow’s great popularity, this theory was quickly accepted in Europe, and then the rest of the world.

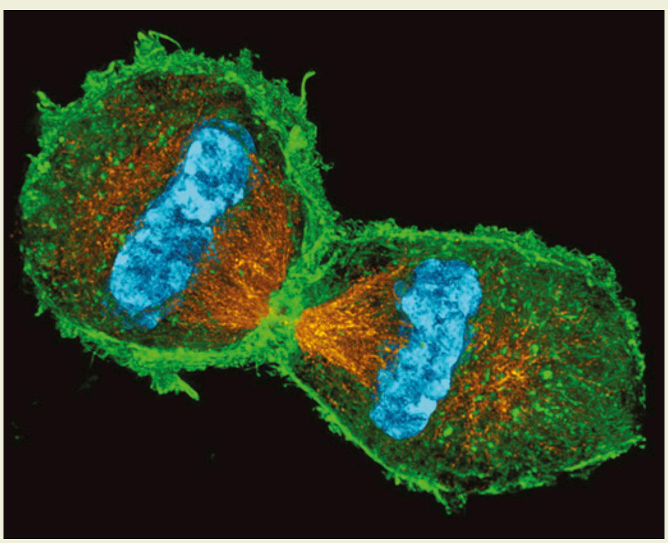


FIGURE 2.4.17 A cell divides to form two cells.

Louis Pasteur: germ theory and pasteurisation

In 1859, the French microbiologist, Louis Pasteur, finally disproved the theory of spontaneous generation. He did so by boiling beef broth in two flasks. Each flask had a curved glass neck to prevent contaminants in the air from reaching the broth (Figure 2.4.18). No microorganisms grew in either of the curved-neck flasks. When the curved neck was broken on one flask and the broth was exposed to the air, microorganisms began to grow in the broth. The unbroken flask remained free of microorganisms, leading Pasteur to reject the hypothesis that life can spontaneously generate.

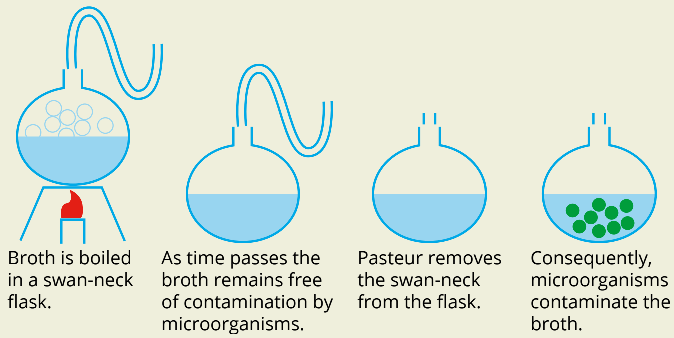


FIGURE 2.4.18 Pasteur’s experiment rejected the theory of spontaneous generation.

Pasteur also showed that boiling and cooling wine or milk killed any microorganisms in the liquid. This process was named after Pasteur and is called pasteurisation.

Pasteur’s experiment provided the scientific basis for the germ theory of infection. This important theory states that germs are widely present in the environment and are the cause of many diseases. Understanding germ theory eventually led to the development of antiseptic procedures in medicine.

2.4 Review

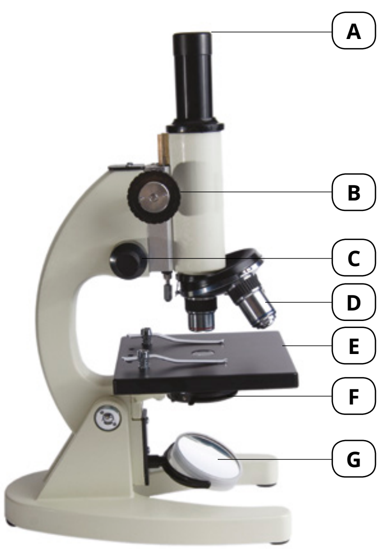
SUMMARY

- Cytology is the study of cells.
- A range of technologies are used to investigate cell structure and function.
- Cells vary greatly in size, and a microscope is needed to see most cells.
- Cells are measured in micrometres (μm). There are 1000 micrometres in 1 millimetre (mm).
- Some typical cell lengths are:
  - bacterium: 0.1–1.5 μm
  - human: 8–60 μm
  - plant: 10–100 μm
  - paramecium (a single-celled eukaryote): about 150 μm.
- Light microscopes use visible light and a system of lenses to magnify images.
  - The fluorescence microscope and confocal microscope are types of light microscopes.
- Electron microscopes use an electron beam, focused by electromagnets, to view objects. They have a much higher magnification and resolution than a light microscope.
  - The transmission electron microscope and scanning electron microscope are types of electron microscopes.
- Autoradiography is a technique used with both light and electron microscopes. Tissue is treated with a radioactively labelled substance that is taken into the part of the cell that is being investigated. This technique allows scientists to identify specific organelles or the location of molecules within a cell or tissue.
- A synchrotron is a large machine in which a beam of electrons, guided by powerful magnets, is accelerated to almost the speed of light. Synchrotron light allows scientists to view structures at the atomic scale.

KEY QUESTIONS

1 The micrometre is the unit used when stating cell sizes. There are 1000 micrometres in a millimetre. Convert 1.6 mm (millimetres) into μm (micrometres).

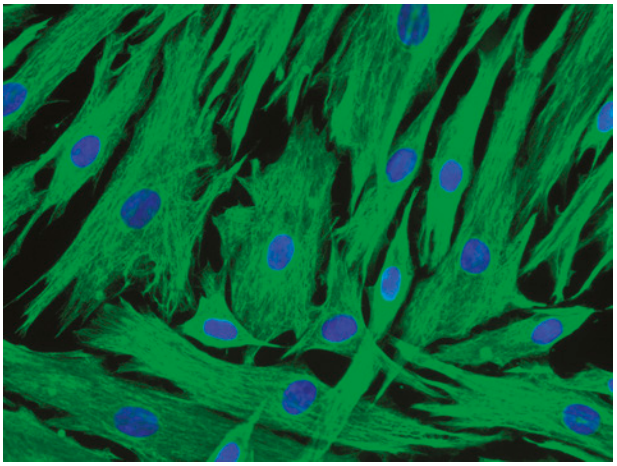
2 Identify the parts of the light microscope labelled A–G in the diagram.



3 What is the main difference between light microscopy and electron microscopy?

4 What is the difference between transmission electron microscopy and scanning electron microscopy?

5 The figure below shows an image of hair follicle cells. Which type of microscope was used to take the image? Explain your answer.



6 What advantages in structural biology are gained by a synchrotron?

7 What advances have been made in science with the help of synchrotron technology?

Chapter review

02

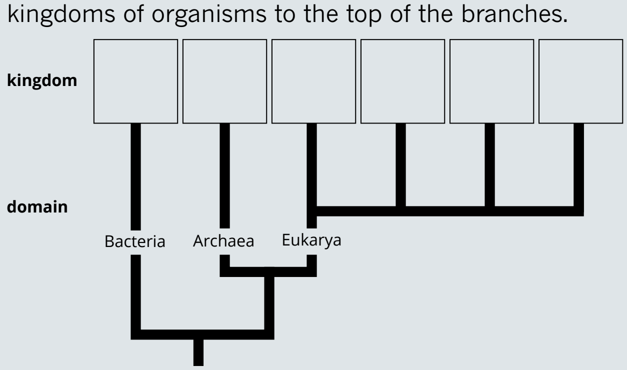
KEY TERMS

Archaea
autoradiography
Bacteria
bilayer
carbohydrate
cell
cell compartmentalisation
cell membrane
cell wall
cellular respiration
centriole
chemosynthesis
chloroplast
cholesterol
chromosome
cis face
cisternae
confocal microscope
cytology
cytoplasm
cytosol
DNA (deoxyribonucleic acid)
domain
electron microscope
endocytosis
endosome
enzyme
Eukarya
eukaryote
exocytosis
external environment
extracellular fluid
extremophile
fimbriae
flagellum
fluid mosaic model
fluorescence microscope
fungi
genophore
glycolipid
glycoprotein
Golgi apparatus
gram-negative
gram-positive
inorganic compound
integral protein
internal environment
intracellular fluid
light microscope
lipid
lysosome
metabolic
mitochondrion (pl. mitochondria)
morphology
multicellular
mRNA (messenger RNA)
nucleoid
nucleolus
nucleus
objective lens
ocular lens
organelle
organic compound
peptidoglycan
peripheral protein
permeable membrane
phospholipid
photosynthesis
plasma membrane
plasmid
plastid
prokaryote
protein
protist
ribosome
rough endoplasmic reticulum
RNA (ribonucleic acid)
rRNA (ribosomal RNA)
scanning electron microscope
section
semipermeable membrane
smear
smooth endoplasmic reticulum
specimen
symbiosis
taxonomy
tonoplast
trans face
transmembrane protein
transmission electron microscope
turgor
unicellular
vacuole
whole mount
xylem

REVIEW QUESTIONS

1 Select the list containing structures that are common to all cells.
A cytoplasm, chloroplasts, DNA, cell membrane
B DNA, ribosomes, cell membrane, cytoplasm
C ribosomes, DNA, mitochondria, cell wall
D cell wall, plastids, DNA, ribosomes

2 Complete the evolutionary tree by adding the six kingdoms of organisms to the top of the branches.



3 Why are Bacteria and Archaea now classified as different domains?

4 What is the difference between gram-positive and gram-negative bacteria?

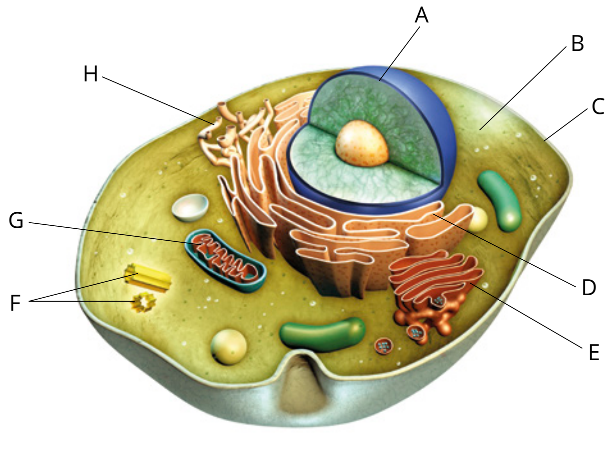
5 Select the statement that accurately describes eukaryotic cells.
A Eukaryotic cells have circular chromosomes and membrane-bound organelles, and some also have cell walls.
B Eukaryotic cells have linear chromosomes but not membrane-bound organelles, and some have cell walls.
C Eukaryotic cells have linear chromosomes and membrane-bound organelles, and some also have cell walls.
D Eukaryotic cells have linear chromosomes and membrane-bound organelles, but not cell walls.

6 A cell from an organism has a distinct nucleus, green organelles, and a cell membrane within a cell wall. In what kingdom is this organism classified?

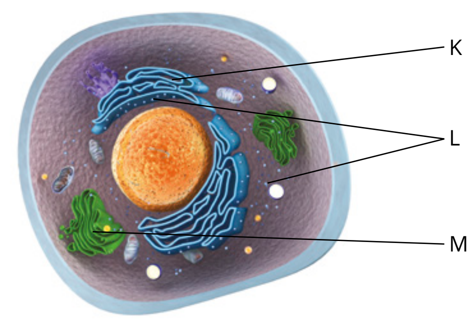
7 Define cell compartmentalisation, and list three ways that it benefits a cell.

8 Cell compartmentalisation makes eukaryotic cells more efficient than prokaryotic cells because:
A it allows tasks to be merged together
B it decreases the surface area of eukaryotic cells
C each compartment is entirely independent of the others
D it allows different areas of the cell to maintain different conditions.

9 Label the parts of the animal cell in this diagram.



10 Examine the cell below.



a Identify the organelles K and M.

b **i** Describe one similarity in function between K and M.

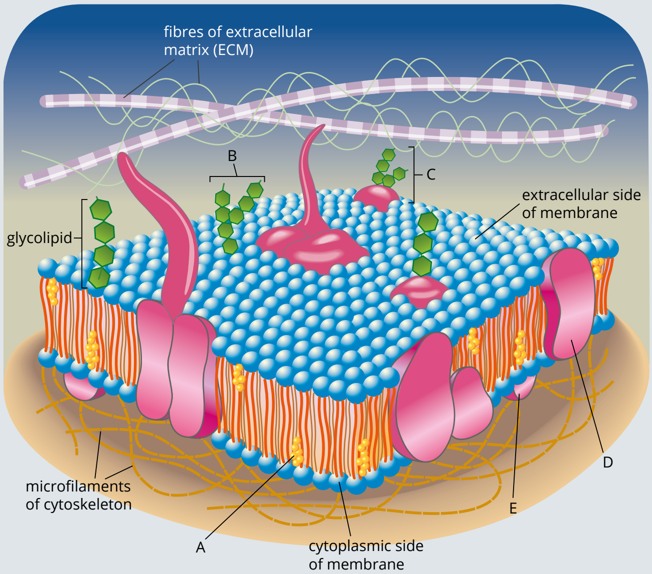
ii Describe one difference in function between K and M.

c A cell contains large numbers of organelle M. Suggest a possible function for the cell, giving a reason for your suggestion.

d How might organelle L be involved in the specialised function of the cell?

11 List three functions of the cell membrane.

12 Label the key components A–E of the cell membrane shown in the diagram below.



13 Outline how the properties of phospholipids form the phospholipid bilayer.

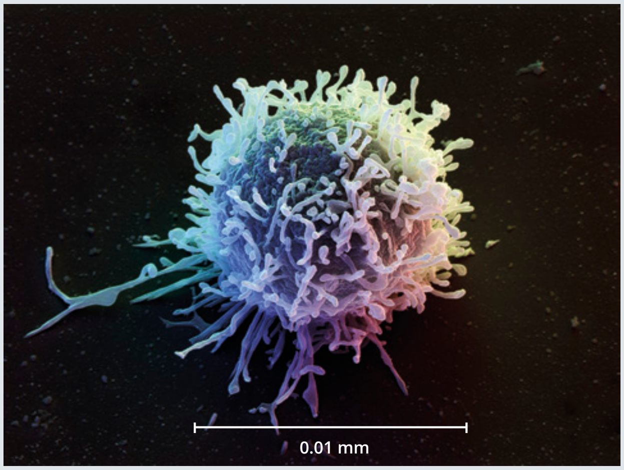
14 Explain why the structure of the cell membrane is described as a 'fluid mosaic'.

15 Explain the factors that can affect the fluidity of the cell membrane.

16 What does cytology study?

A cytosol
B tonoplasts
C cells
D cytoplasm

17 Select the answer that is closest to the diameter of the animal cell shown in the following photograph.



A 10 μm
B 100 μm
C 1 μm
D 1000 μm

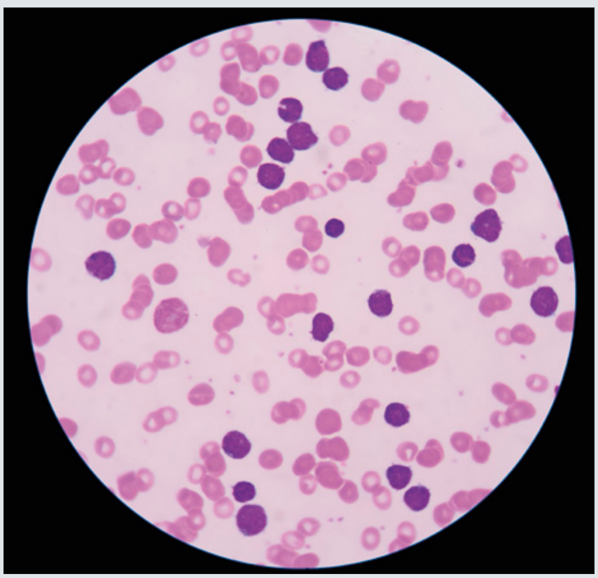
18 You are given a microscope slide with a sample of cells smeared on it and asked to identify the cell type. The cells are circular with a dark, round mass at their centre. You estimate that the cells are approximately 20 μm in diameter.

a Are the cells prokaryotic or eukaryotic? What feature(s) led you to your conclusion?

b What is the dark, round mass at the centre of the cells?

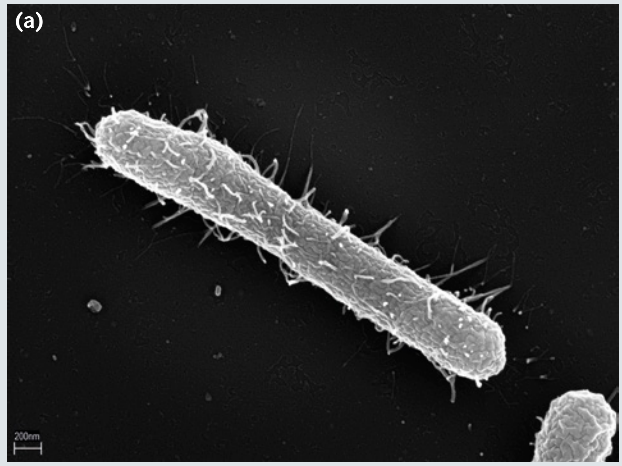
c What are three features you could look for to determine if the cells are from a plant or an animal?

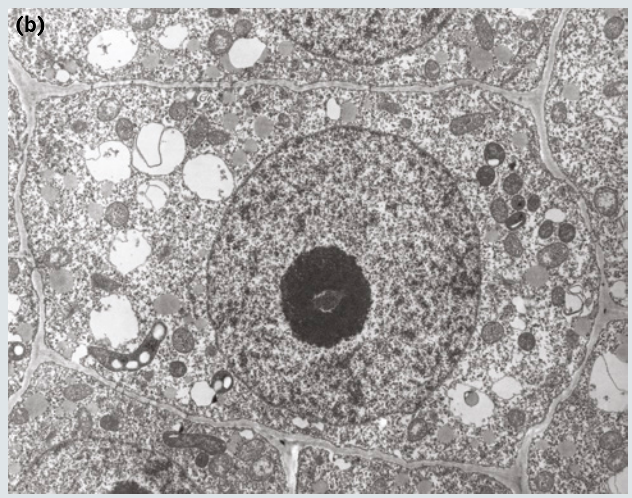
19 Below is an image of a cell smear that contains a high number of abnormal white blood cells, indicating leukaemia (cancer). The white blood cells are the large, dark, purple-stained cells and the smaller pink cells are normal red blood cells. There are approximately 207 normal red blood cells. Count the number of white blood cells and calculate the percentage of each cell type.



20 Electron microscopes greatly magnify the internal structure of cells, and have therefore improved our understanding of cellular structures.

Below are two cells observed under an electron microscope; (a) is from a scanning electron microscope and (b) is from a transmission electron microscope.





a One of the two cells is from a prokaryote. Explain which one.

b Is the eukaryotic cell from an animal or a plant? Give a reason for your choice.

21 After completing the Biology Inquiry on page 68, reflect on the inquiry question: What distinguishes one cell from another? Explain how prokaryotic cells are different from eukaryotic cells and outline the advantages and disadvantages of each cell type.

CHAPTER

03 Cell function

This chapter examines the coordination of cellular functions within their internal and external environments. You will investigate how materials move into and out of cells via diffusion, osmosis, active transport, endocytosis and exocytosis. You will also learn about how surface-area-to-volume ratio, concentration gradients and the characteristics of materials are related to the exchange of materials across the cell membrane. The requirements of cells, including energy, matter and waste removal will be examined, along with the biochemical processes of photosynthesis and cellular respiration. You will also learn about enzyme action in cells, and the effects of the environment on enzyme activity.

Content

INQUIRY QUESTION

How do cells coordinate activities within their internal environment and the external environment?

By the end of this chapter you will be able to:

- investigate the way in which materials can move into and out of cells, including but not limited to:
  - conducting a practical investigation modelling diffusion and osmosis (ACSBL046) ICT
  - examining the roles of active transport, endocytosis and exocytosis (ACSBL046)
  - relating the exchange of materials across membranes to the surface-area-to-volume ratio, concentration gradients and characteristics of the materials being exchanged (ACSBL047) ICT N
- investigate cell requirements, including but not limited to:
  - suitable forms of energy, including light energy and chemical energy in complex molecules (ACSBL044)
  - matter, including gases, simple nutrients and ions
  - removal of wastes (ACSBL044)
- investigate the biochemical processes of photosynthesis, cell respiration and the removal of cellular products and wastes in eukaryotic cells (ACSBL049, ACSBL050, ACSBL052, ACSBL053) ICT
- conduct a practical investigation to model the action of enzymes in cells (ACSBL050)
- investigate the effects of the environment on enzyme activity through the collection of primary or secondary data (ACSBL050, ACSBL051) ICT N

3.1 Movement of materials in and out of cells

In Section 2.3, you learnt about the composition of the cell membrane, and that one of its main functions is to control the transport of molecules between the cell's internal environment (the cytosol) and the external environment. The way in which materials cross the cell membrane depends on the:

- characteristics of the materials being exchanged
- permeability of the cell membrane to the material (Table 3.1.1)
- surface-area-to-volume ratio of the membrane
- concentration gradient between the internal and external environments of the cell.

In this section, you will learn about the semipermeability of the cell membrane. You will also explore the various methods cells use to control the exchange of molecules, including diffusion, osmosis, active transport, facilitated diffusion, endocytosis and exocytosis.

CELL MEMBRANE PERMEABILITY

The permeability of a **cell membrane** refers to its ability to allow the cell to exchange liquids and materials between the cell's **internal environment** and the **external environment**. The movement of materials in and out of a cell is critical to its function and survival, allowing essential materials to enter while keeping **waste** materials out. It also allows cells to communicate with other cells.

The cell membrane is selective about the materials that it allows in and out of the cell. This characteristic is known as semipermeability. Many different types of **molecules** can move across cell membranes (Figure 3.1.1). They do so in different ways depending on their characteristics, such as size and charge, and the permeability of the cell membrane to the material (Table 3.1.1).

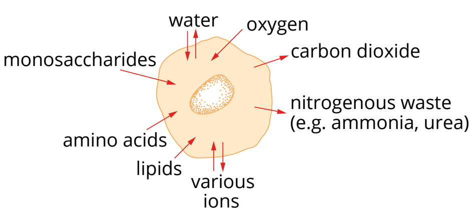


FIGURE 3.1.1 Cells exchange many substances with their environment across the cell membrane.

TABLE 3.1.1 The permeability of cell membranes to different molecules

Molecule/ion	Examples	Permeability of membrane to the molecule/ion
small, uncharged molecule	oxygen, carbon dioxide	permeable
lipid-soluble, non-polar molecule	alcohol, chloroform, steroids	permeable
small, polar molecule	water, urea	permeable or semipermeable
small ion	potassium ion (K^+), sodium ion (Na^+), chloride ion (Cl^-)	impermeable (ion passes through protein channels)
large, polar, water-soluble molecule	amino acid, glucose	impermeable (molecule passes through protein channels)

Because of their lipid nature, cell membranes are permeable to small molecules and lipid-soluble molecules that can move freely through the **phospholipid** bilayer. However, their lipid nature also makes cell membranes impermeable to:

- most water-soluble molecules
- ions (atoms or groups of atoms with an overall positive or negative charge)
- polar molecules (molecules with charged regions but no overall charge).

These substances must therefore pass through specific protein channels in the cell membrane (Figure 3.1.2).

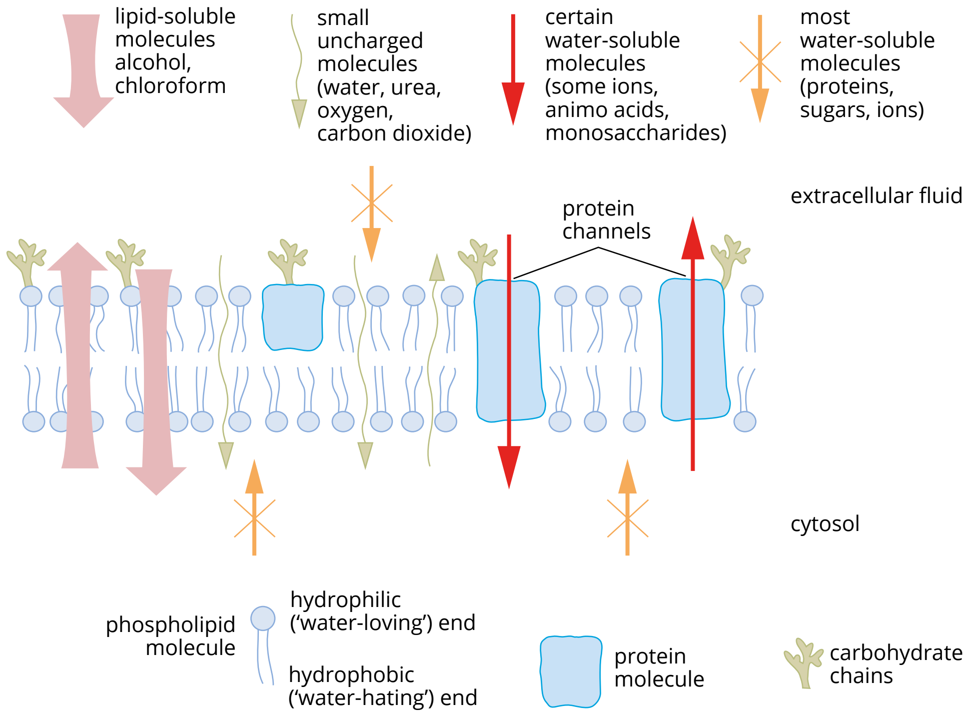


FIGURE 3.1.2 If the cell membrane is not permeable to molecules, protein channels must help the molecules cross the membrane.

DIFFUSION

Particles in a solution move from an area of high concentration to an area of low concentration. This process is called **diffusion** (Figure 3.1.3). Because many particles collide with each other during this process, the overall movement of particles is very slow.

Diffusion can be seen when a drop of ink (the **solute**) is placed in a jar of still water (the **solvent**). The dye particles in the ink move randomly through the water until the colour is homogenous (evenly spread). In other words, the solute particles move from an area of high solute concentration (the drop of ink) to the areas of low solute concentration (the rest of the jar). The solute particles are said to have moved along the **concentration gradient**.

Diffusion is called a passive process, because it does not require energy. It occurs only because there is a concentration gradient.

> When particles move from an area of high concentration to an area of low concentration, they are moving along a concentration gradient.

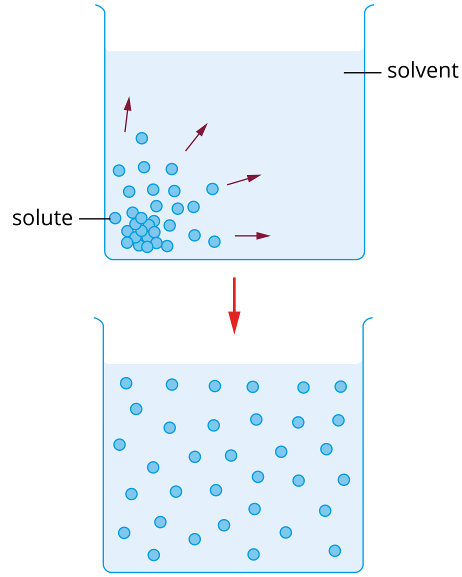


FIGURE 3.1.3 Diffusion results in the random dispersal of solute molecules throughout a solvent.

DIFFUSION ACROSS MEMBRANES

The two types of diffusion across membranes are **simple diffusion** and **facilitated diffusion**. These are both passive types of diffusion, and both move molecules along the concentration gradient.

Simple diffusion

Solute molecules can only diffuse across a membrane if that membrane is permeable to them. There is a constant movement of solute molecules backwards and forwards across the membrane.

If the concentration of solute molecules is the same on both sides of the membrane, there will always be about the same number moving across in either direction.

BIOFILE PSC

The diffusion of alcohol molecules

Alcohol enters the bloodstream quickly. It is a non-polar molecule that does not need to be broken down into smaller molecules by digestion, and passes across membranes easily by simple diffusion (Figure 3.1.5). As a result, alcohol molecules are absorbed rapidly by the mouth, stomach and small intestine, where absorption is fastest. Eating a meal before drinking reduces the efficiency and rate of alcohol absorption. A blood test for alcohol may be used after a road accident or violent crime.

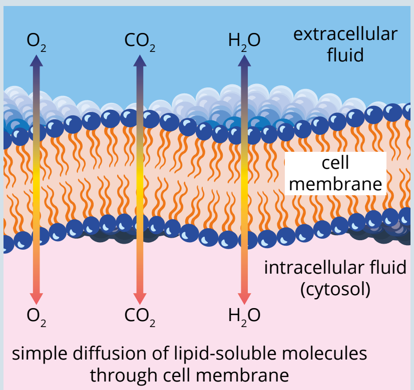


FIGURE 3.1.5 The transport of materials across the cell membrane by simple diffusion

Rates of diffusion across cell membranes vary depending on solute concentration, temperature and the size of molecules. For example, at body temperature, water molecules travel at about 2500 km/h. Glucose, a larger molecule, travels more slowly at only about 850 km/h.

That is, there will be no net movement from one side to the other. However, if the concentration of the solute molecule is higher on one side of the membrane than the other, more molecules will cross from the area of higher concentration to the area of lower concentration (i.e. down its concentration gradient) (Figure 3.1.4a).

If the membrane is **semipermeable**—that is, it is impermeable to some molecules—there will be no movement of those molecules from the area of higher concentration to the area of lower concentration (Figure 3.1.4b).

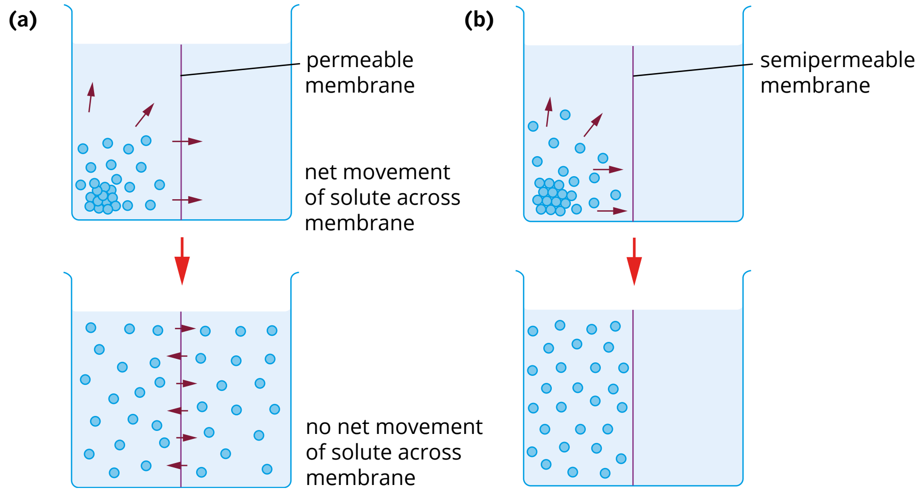


FIGURE 3.1.4 (a) If a membrane that is permeable to both the solute and the solvent is inserted in the liquid, it does not affect the pattern of diffusion. (b) A membrane that allows the solvent molecules to pass through, but not the solute molecules, stops the solute from diffusing through the membrane.

Factors affecting rate of diffusion

Three main factors affect the rate of diffusion across a membrane:

- Concentration—the greater the difference in concentration gradient, the faster the rate of diffusion. When the concentration is equal on both sides of the membrane, the net diffusion is zero, even at high temperatures.
- Temperature—the higher the temperature, the higher the rate of diffusion. Increasing temperature increases the speed at which molecules move.
- Particle size—the smaller the particles, the faster the rate of diffusion.

Facilitated diffusion

The phospholipid bilayer of the membrane is impermeable to certain particles (ions or molecules). However, channel proteins in the membrane allow for the movement of these particles. When movement is down the concentration gradient, the process is called facilitated diffusion.

In facilitated diffusion:

- The membrane transport proteins are specific for particular particles, so transport is selective; some particles are transported and others are not.
- Transport is more rapid than by simple diffusion.
- The transport proteins can become saturated (fully occupied) as the concentration of the transported substances increases.
- The transport of one particle may be inhibited by the presence of another particle that uses the same transport protein.
- No energy is required; the particles move down their own concentration gradient.

The two main types of membrane transport proteins involved in facilitated diffusion are **channel proteins** and **carrier proteins**. Membrane proteins provide channels for the passage of water-soluble (polar) molecules and ions across the phospholipid bilayer. The channel proteins are specific for a substance. Channel proteins do not usually bind with the molecules being transported. They function like pores that open and close to allow the passage of specific molecules. Channel proteins are mainly involved in the passage of water-soluble polar particles, such as ions (e.g. Na^+, K^+ and Cl^-).

Carrier proteins bind the molecules being transported. This causes the protein to undergo changes in shape (or conformation) that allow specific molecules to be transported across the membrane. After the molecule has crossed the membrane, the original shape of the protein is restored.

OSMOSIS

Osmosis refers to the net diffusion of water molecules across a semipermeable membrane.

If a diluted and a concentrated solution are separated by a semipermeable membrane that allows the movement of free water molecules across the membrane, but not the movement of the solute molecules, the free water molecules will move across the membrane from the diluted to the concentrated solution.

In osmosis, net diffusion of water occurs through a semipermeable membrane from a diluted to a concentrated solution along its own concentration gradient. This is known as the **osmotic gradient** (Figure 3.1.6). The pressure causing the water to move along this gradient is called **osmotic pressure**.

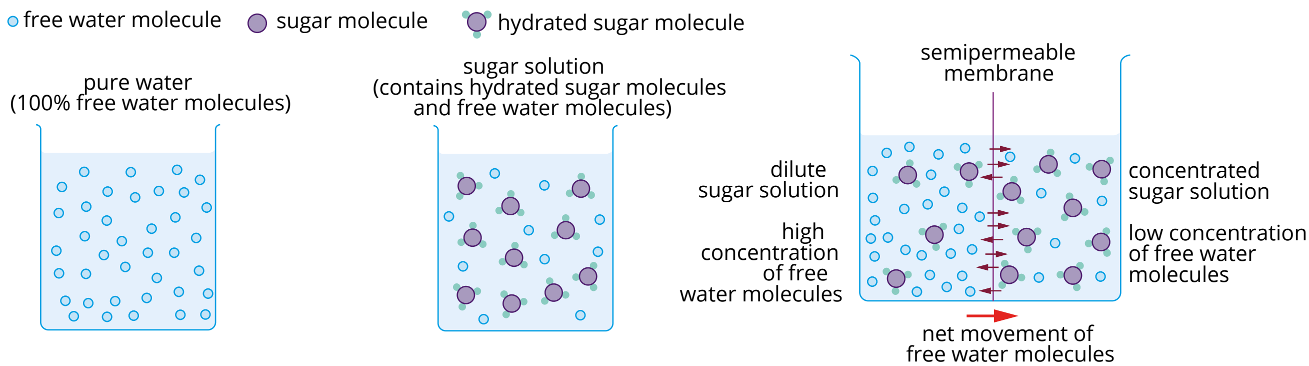


FIGURE 3.1.6 Osmosis describes a net movement of water molecules from a dilute solution through a semipermeable membrane into a concentrated solution.

The cell membrane is permeable to water. Therefore, when cells are placed in freshwater, an osmotic gradient will draw water into the cells. This is because the cytosol is a concentrated solution containing many dissolved substances.

For example, if red blood cells are placed in freshwater, the cells absorb so much water by osmosis that they swell and may eventually burst, releasing red pigment into the water (Figure 3.1.7). Conversely, if red blood cells are placed in a solution that is more concentrated than their cytosol, water leaves the red blood cells by osmosis, causing them to shrink.

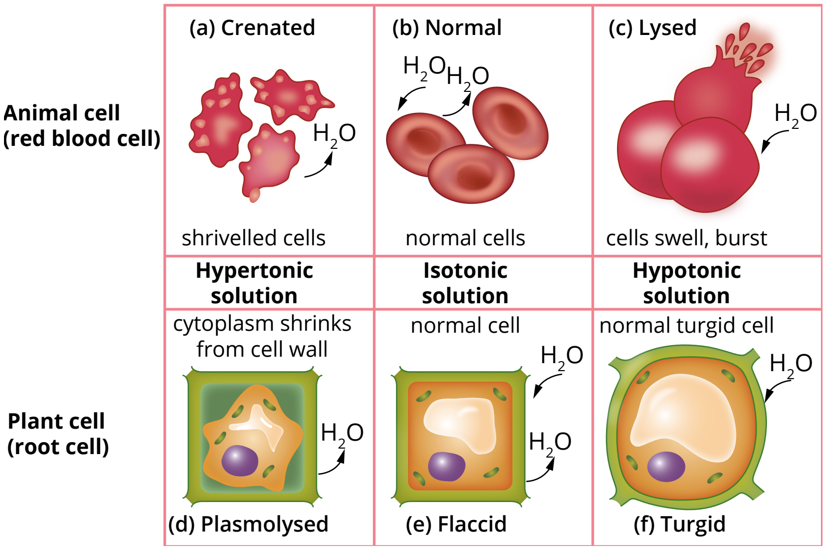


FIGURE 3.1.7 The effect of three different solution concentrations on an animal cell and plant cell

If a plant cell absorbs water, it swells to some extent, but the cell wall prevents the cell from bursting (Figure 3.1.7). Water will continue to enter the cell along an osmotic gradient until the internal fluid pressure equals the osmotic pressure drawing water in, at which point no more water will enter. Plant cells with high internal fluid pressures are said to have a high turgor, or be turgid.

In osmosis, we always compare solute concentration between two solutions. The terms isotonic, hypertonic and hypotonic are often used to describe the differences between solutions.

- **Isotonic solutions—**the solutions being compared have equal concentration of solutes.
- **Hypertonic solution—**the solution with a higher concentration of solute (hence lower concentration of free water molecules).
- **Hypotonic solution—**the solution with a lower concentration of solute (hence higher concentration of free water molecules).

FIGURE 3.1.8 This pink salt lake owes its distinctive colour to the presence of red algae and the solid salt bed of the lakes.

PA 1.3 PA 1.3

Osmosis in salty environments

There is no biological mechanism for actively transporting water molecules across cell membranes. The net movement of water across membranes occurs only by osmosis. Some bacteria, known as halophiles, are adapted to extremely salty environments, such as the pink salt lakes in western New South Wales (Figure 3.1.8). They survive by retaining much higher ion concentrations within their cells. They also produce small, osmotically active but otherwise inert molecules to reduce the osmotic gradient. This prevents the loss of water to their salty surroundings. Their proteins are also specialised to function normally, despite the high concentration of salts in the cytosol.

ACTIVE TRANSPORT

Diffusion, facilitated diffusion and osmosis are examples of **passive transport**, because they do not require energy to move particles across the cell membrane. **Active transport** involves the cell using energy to transport particles across membranes (Figure 3.1.9).

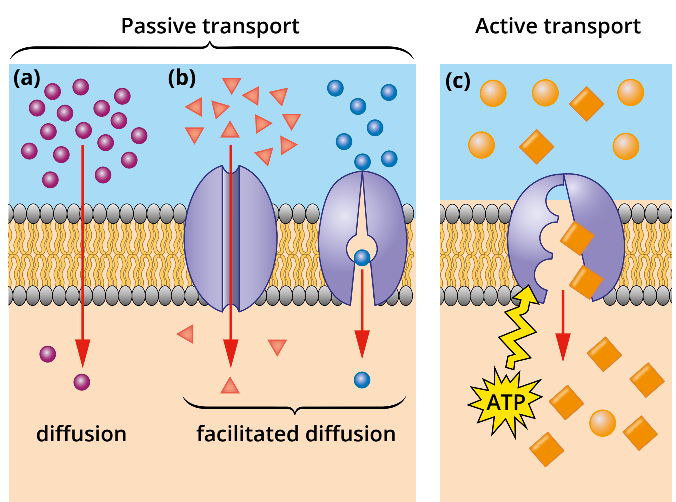


FIGURE 3.1.9 Passive transport across a cell membrane does not require an energy source, and can occur (a) as diffusion, where substances move from high to low concentrations, or (b) facilitated diffusion, where substances move from high to low concentrations with help from a carrier protein. Active transport requires an energy source, and usually moves substances from low to high concentrations. Image (c) shows a protein pump that helps substances cross the membrane.

Active transport and facilitated diffusion compared

Active transport has the same properties of selectivity, saturation and **competitive inhibition** as facilitated diffusion, because it also occurs through transport proteins (Figure 3.1.10).

- Selectivity means that some substances are transported but others are not.
- Saturation means that there is no increase in the rate of transfer when all transport proteins are open.
- Competitive inhibition means that one substance can inhibit the transport of another substance by using the same transport protein.

However, unlike facilitated diffusion, which can occur through either channel or carrier proteins, active transport only occurs through carrier proteins. Because active transport uses energy, it can move substances against a concentration gradient (from low concentrations to high concentrations). In comparison, facilitated diffusion uses no energy, so it can only move substances down a concentration gradient.

In different situations, either facilitated diffusion or active transport may be used to transport a particular molecule. Whether a cell uses facilitated diffusion or active transport depends on the specific needs of the cell.

For example, **glucose** is actively transported from the gut into epithelial cells lining the gut, so it can enter the bloodstream. The regulation of this process is controlled by hormones, principally insulin and glucagon. If gut glucose levels are high, blood glucose levels will increase. If gut glucose levels are low, active transport makes sure that the little glucose that is in the gut gets pumped into the **epithelium**. From the epithelium, the glucose can move into the blood via facilitated diffusion.

In contrast, red blood cells move glucose by facilitated diffusion. This makes sense, because glucose concentration in the blood is usually maintained within a narrow range. In addition, cells convert glucose into other chemicals as soon as it enters the cell. This keeps the intracellular concentration of glucose lower than the blood concentration of glucose, meaning that the concentration gradient is maintained in favour of glucose entering the cell.

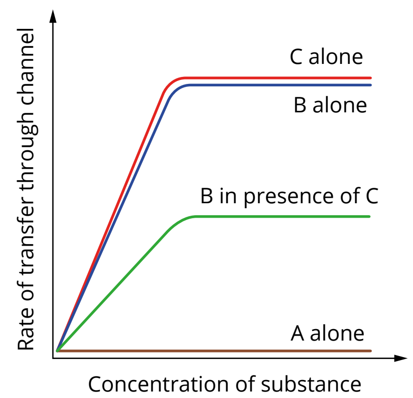


FIGURE 3.1.10 Theoretical transport rate vs concentration graph for the movement of three substances—A, B and C—through a channel protein. Substances B and C are transported, but not substance A, demonstrating selectivity. The rate of transfer of substances B and C flattens out when their concentrations reach a certain level, demonstrating saturation. The rate of transport of B is less when C is present, demonstrating competitive inhibition.

ENDOCYTOSIS AND EXOCYTOSIS

Some large molecules and other particles and fluids are moved into or out of the cell by **endocytosis** and **exocytosis** (Figure 3.1.11). These are both forms of active transport, because they require energy.

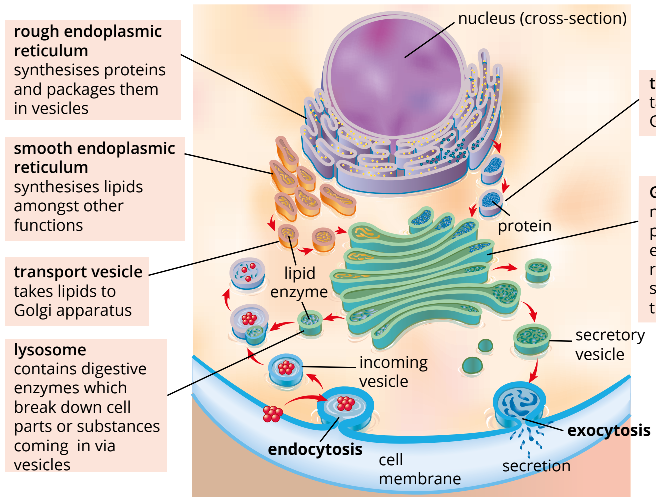


FIGURE 3.1.11 To transport large molecules that proteins or pumps cannot transport, cells use endocytosis and exocytosis, which require energy and the formation of vesicles.

Endocytosis

In endocytosis, the cell takes in materials in bulk by forming new **vesicles** from the cell membrane. During endocytosis, a small area of the cell membrane sinks inwards to form a pocket. As the pocket deepens, materials near the cell membrane are enclosed by the membrane, which then pinches off to form a vesicle. The vesicle then transports the substance to where it is required within the cell.

There are three types of endocytosis (Figure 3.1.12):

- In **phagocytosis**, a cell engulfs a solid material by wrapping temporary cytoplasmic extensions called **pseudopodia** (meaning 'false feet') around it. This forms a membrane-bound structure known as a **phagosome** (Figure 3.1.13). The material will be digested when the food vacuole fuses with a **lysosome** that contains **enzymes**.
- In **pinocytosis**, the cell membrane engulfs liquid that contains dissolved molecules (Figure 3.1.14).
- **Receptor-mediated endocytosis** is a type of pinocytosis that engulfs specific substances. Protein **receptors** located on the surface of the cell membrane respond to particular molecules, binding to the molecule and triggering the engulfment of the substance into the cell.

FIGURE 3.1.13 A coloured scanning electron microscope (SEM) image of a macrophage white blood cell (white and purple) engulfing a tuberculosis bacterium (*Mycobacterium tuberculosis*) (pink) by phagocytosis

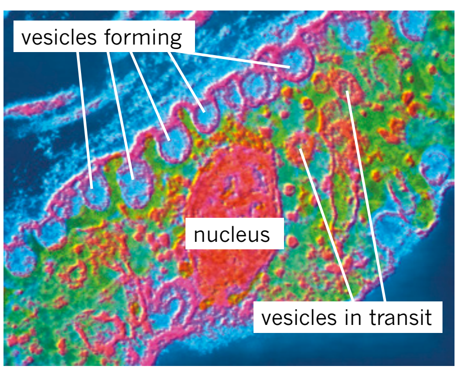


FIGURE 3.1.14 A transmission electron microscope (TEM) image showing pinocytosis in a blood capillary. The lumen (inner space) of the capillary is at the top (blue), with one of the endothelial cells of the capillary lining below, the nucleus of which is red. A row of the vesicles formed during pinocytosis can be seen in the upper cell membrane (pink) and in transit towards the outside of the capillary (bottom).

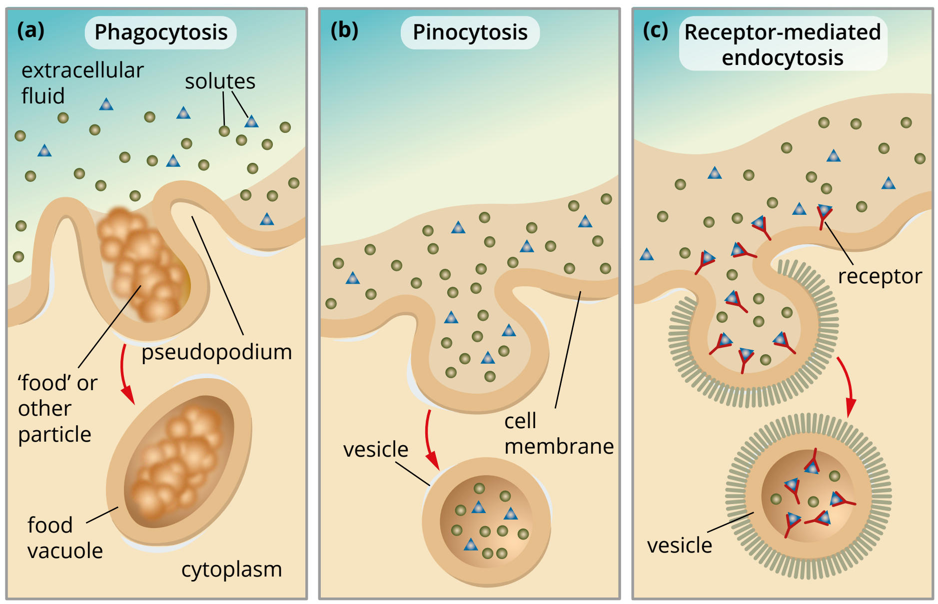


FIGURE 3.1.12 The three types of endocytosis, (a) phagocytosis, (b) pinocytosis and (c) receptor-mediated endocytosis, showing the engulfment of different materials by the cell membrane and the release of the vesicle within the cell

Exocytosis

When a secretory vesicle membrane and the cell membrane come into contact, specific proteins alter the arrangement of the phospholipids in the phospholipid bilayer. The fluid and dynamic nature of the cell membrane then enables the two membranes to fuse. Once the membranes have fused, the contents of the secretory vesicle are released out of the cell. This is called exocytosis.

The vesicle membrane becomes a permanent part of the cell membrane (Figure 3.1.15). The cell membrane is continually recycled as vesicles fuse during exocytosis, and are conversely formed and released during endocytosis.

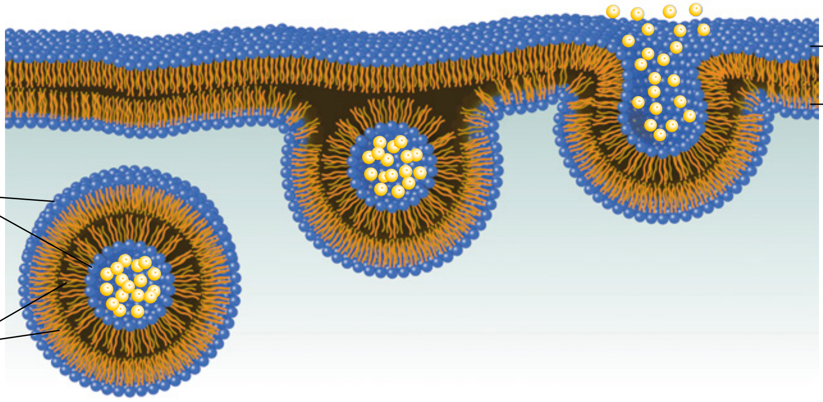


FIGURE 3.1.15 Exocytosis is the movement of a secretory vesicle towards the cell membrane and the release of its contents.

In addition to being used for secreting proteins, exocytosis is also involved in the release of cellular waste and the breakdown products from lysosomes. For example, phagocytic cells (such as unicellular protists or macrophages in multicellular organisms) engulf food or foreign matter and digest them with the aid of lysosomes. Afterwards, the waste products of this digestion are released by exocytosis.

WS 1.5

A summary of the roles of the rough endoplasmic reticulum and Golgi apparatus in the exocytosis of proteins can be seen in Figure 3.1.11.

BIOLOGY IN ACTION ICT

Making artificial pores from carbon nanotubes

The cell membrane plays a vital role in the protection of the internal cellular environment and the transport of substances vital to cell growth, communication and survival. The selectively permeable nature of the cell membrane enables tight regulation of what can and cannot enter and exit the cell.

Synthetic membranes are used widely in medicine (e.g. kidney dialysis tubing), research laboratories and industry for separation and purification purposes (e.g. water treatment). However, until recently, scientists have not been able to mimic the selective permeability of cell membranes.

Researchers at the University of California have developed carbon nanotubes that can be inserted into both synthetic and natural membranes (Figure 3.1.16), creating artificial pores. Carbon nanotubes are thin cylinders of carbon atoms. The researchers used lipids to refine the structure of the nanotubes, ensuring that they were just the right size and composition to penetrate the membrane. Because cell membranes consist of a lipid bilayer in which lipid and protein molecules are embedded, the nanotube structure needed to be consistent with this. The researchers coated the nanotubes with lipids, which allowed them to slide into the cell membrane of a cell without causing damage.

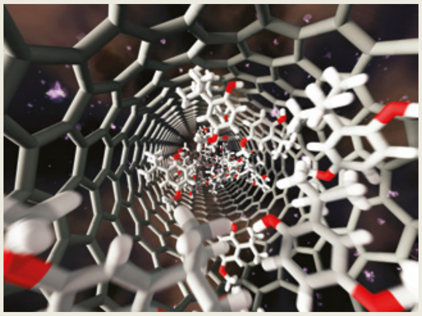


FIGURE 3.1.16 Nanotube technology provides the potential for drugs to be delivered to specific tissues and cells.

The researchers also observed the nanotubes opening and closing, just like biological ion channels. They discovered that the charge of the ends of the nanotubes shifted in response to changes in the ion concentration of the surrounding environment. These properties of nanotubes make it possible for scientists to artificially control what enters and exits cells. Potential applications of this research lie in areas such as drug delivery, where the selective transport of molecules could significantly improve treatment.

SURFACE-AREA-TO-VOLUME RATIO

All cells must exchange nutrients and wastes with their environment via the cell membrane. In addition, enzymes that are bound to the cell membrane **catalyse** many important cellular processes. The surface area of the cell membrane around a cell affects the rate of exchange that is possible between the cell and its environment, and can affect certain processes catalysed by membrane-bound enzymes.

Larger cells have greater metabolic needs, so they need to exchange more nutrients and waste with their environment. However, as the size of a cell increases, the **surface-area-to-volume ratio** of the cell decreases.

A large surface-area-to-volume ratio is one of the most important features of cells.

Because of this surface-area-to-volume relationship, larger cells do not have a proportionally larger surface area of cell membrane for the efficient exchange of nutrients and waste. Smaller cells can exchange matter with their environment more efficiently.

SKILLBUILDER CCT N

Calculating surface-area-to-volume ratio

As the size of an object increases, its surface-area-to-volume ratio decreases. The relationship between surface area and volume can be explained using cubes. The cube in Figure 3.1.17 has a length, width and height of 1 m, giving each of its six sides an area of 1 m^2. This gives the cube a total surface area of 6 m^2 (6 × 1 m^2). To calculate the volume of the cube, its length is multiplied by its width and its height: 1 m × 1 m × 1 m = 1 m^3. With a surface area of 6 m^2 and a volume of 1 m^3, the cube has a surface-area-to-volume ratio of 6:1 or 6.

If the cube is cut into eight 0.5 m cubes, each cube side has a surface area of 0.25 m^2. This gives each smaller cube a total surface area of 1.5 m^2 (6 × 0.25 m^2) and a combined surface area of 12 m^2 (8 × 1.5 m^2). Cutting the big cube into smaller cubes has doubled the surface area but the total volume of all the cubes stays the same (1 m^3) (Figure 3.1.17). This is because parts of the cube that were originally on the inside of the cube have now become part of the surface. The same 1 m^2 cube divided into 1 μm cubes has a surface area of 6 000 000 m^2 but the volume is still 1 m^3.

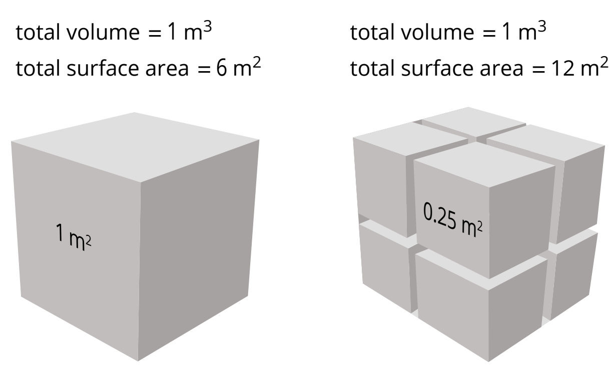


FIGURE 3.1.17 When a 1 m cube is divided into eight equal cubes, the volume stays the same, but the surface area doubles. This shows the relationship between surface area and volume.

Increasing the cell surface-area-to-volume ratio

Three ways of increasing the membrane surface area of cells without changing cell volume are:

- **cell compartmentalisation**
- a flattened shape
- cell membrane extensions.

Cell compartmentalisation

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In Section 2.2, you learnt that cell compartmentalisation allows organelles to have the right conditions and concentration of enzymes and reactants for a particular function, making the processes in the organelles—and in turn, the whole cell—highly efficient.

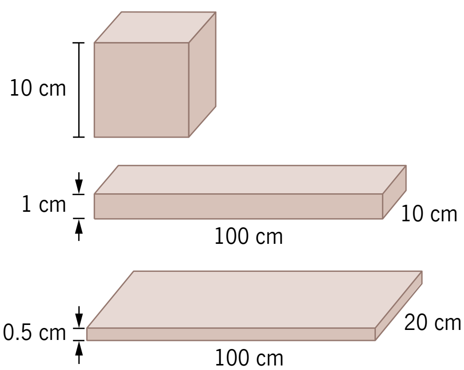
Cell compartmentalisation also allows eukaryotic cells to be much bigger than prokaryotic cells, because it:

- reduces the amount of exchange that needs to occur across the cell membrane to maintain an environment suitable for all cell functions
- creates more space for membrane-bound enzymes, allowing increased activity in the cell.

A flattened shape

As a cell increases in volume, the distance from the centre of the cell to the cell membrane also increases. The rate of chemical exchange (or rate of diffusion) from the centre of the cell to the surrounding environment may then become too low to maintain the cell.

One way to counteract this effect is to be flatter. For example: flattening a cube while keeping the volume constant results in a larger surface area, and therefore a larger surface-area-to-volume ratio (Figure 3.1.18). This larger surface-area-to-volume ratio allows a higher rate of exchange through the cell membrane. It also reduces the distance that substances need to be transported to and from the cell membrane.



Surface area	Volume	Surface-area-to-volume ratio
600 cm^2	1000 cm^3	0:6
2220 cm^2	1000 cm^3	2:2
4120 cm^2	1000 cm^3	4:1

FIGURE 3.1.18 The effect of changing shape on the surface-area-to-volume ratio

The flattened-shape solution is observed in nature in many types of cells—especially those involved in the rapid transport of substances, such as red blood cells and lung epithelium. These cell types do not usually have a high metabolism and so do not contain many organelles.

Cell membrane extensions

Instead of being larger or flatter, cells involved in absorbing nutrients or secreting wastes counteract the surface-area-to-volume ratio problem by extending the surface area of their cell membranes. For example, some animal cells have finger-like extensions of the cell membrane called microvilli (singular **microvillus**), which increase the surface area (Figure 3.1.19). Another example is **root hairs** in plants, which are lateral extensions of root cells. The hairs increase the surface area of the root, allowing the plant to absorb more water and nutrients from the soil.

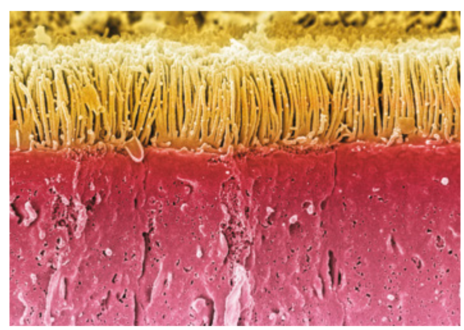


FIGURE 3.1.19 SEM image of microvilli in the small intestine, where digested food is absorbed

PA 1.2

A flattened shape would not be useful for cells involved in absorbing nutrients or secreting wastes, because they require an increased surface area in particular regions of the cell. For example, in cells of the small intestine, an increased surface for exchange is only required on the inside of the intestinal tube, where the cells absorb nutrients. In addition, these cells have a high metabolism and possess many organelles. If they were flattened, the distance between the different organelles of the cell would affect the movement of substances within the cell and reduce its functionality.

3.1 Review

SUMMARY

- The cell membrane is semipermeable. This means it is selective about the materials that it allows in and out of the cell.
- Transport of molecules across the membrane depends on their chemical and physical properties—such as size, charge and polarity—and whether or not the phospholipid bilayer is permeable to the substance.
- Membranes are impermeable to most water-soluble molecules, ions and polar molecules. These substances can only pass through protein channels.
- Lipid-soluble substances can diffuse through the phospholipid bilayer.
- Passive transport is the movement of molecules without the expenditure of energy. Passive transport includes:
  - simple diffusion
  - osmosis
  - facilitated diffusion.
- Diffusion is the passive movement of solute molecules along a concentration gradient, from a region of high solute concentration to a region of low solute concentration.
- There are two types of diffusion across cell membranes: simple and facilitated.
  - Simple diffusion involves solutes that the membrane is permeable to, including lipid-soluble substances, small molecules and water molecules. The rate of diffusion is affected by concentration, temperature and particle size.
  - Facilitated diffusion is through selective channels in membranes that permit or increase the passive movement of particular ions and molecules down their own concentration gradient. Facilitated diffusion generally occurs at a more rapid rate than simple diffusion.
- Osmosis is the net diffusion of water across a semipermeable membrane down its own concentration gradient, called the osmotic gradient (that is, from a low solute concentration to a high solute concentration).
- Active transport is the movement of molecules through protein channels with the expenditure of energy, against the concentration gradient.
- Exocytosis (moving substances out of the cell) and endocytosis (moving substances into the cell) are forms of active transport involving vesicles that fuse with the cell membrane. These forms of active transport are generally used to transport larger molecules.
- Substances can enter a cell by endocytosis. The membrane surrounds and engulfs the substance, forming a vesicle, which enters the cell. There are three types of endocytosis:
  - Phagocytosis—solid particles are engulfed by the cell membrane.
  - Pinocytosis—liquid containing dissolved molecules is engulfed by the cell membrane.
  - Receptor-mediated endocytosis—a type of pinocytosis in which the cell membrane engulfs specific substances that are bound to receptors.
- Exocytosis is the movement of a secretory vesicle towards the cell membrane and the release of its contents.
- As the size of an object decreases, its surface-area-to-volume ratio increases.
- The higher the surface-area-to-volume ratio of an object, the more efficiently it can exchange materials across its surface.
- The cell surface area (cell membrane area) can be increased without varying the cell volume in three ways:
  - compartmentalisation
  - a flattened shape (e.g. red blood cells)
  - cell membrane extensions (e.g. microvilli and root hairs in plants).

KEY QUESTIONS

1 Complete the following table by stating whether the phospholipid bilayer is permeable, semipermeable or not permeable to each substance described.

Substance	Examples	Permeability
small, uncharged molecule	oxygen, carbon dioxide	
lipid-soluble, non-polar molecule	alcohol, chloroform, steroids	
small, polar molecule	water, urea	
small ion	potassium ion (K^+), sodium ion (Na^+), chloride ion (Cl^-)	
large, polar, water-soluble molecule	amino acid, glucose	

2 Describe diffusion and explain the difference between simple and facilitated diffusion. Include an example of each.

3 What are the two types of proteins used in facilitated diffusion, and how are they different?

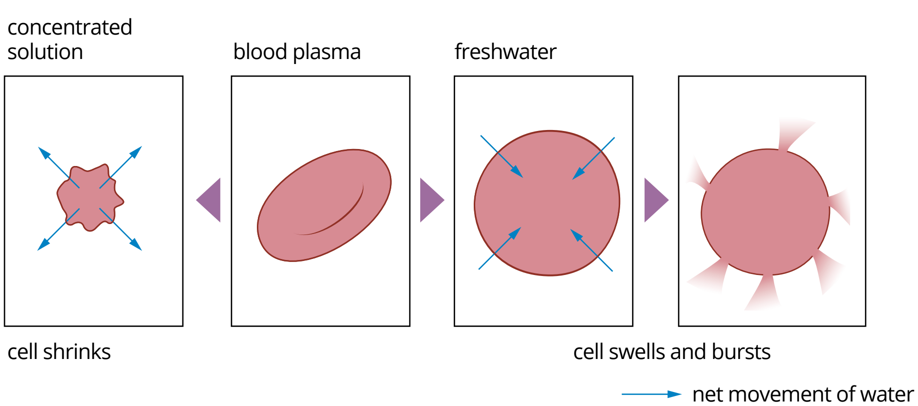
4 What term is used for the net movement of water from a dilute to a concentrated solution down its own concentration gradient?

5 Define the term 'active transport'. Outline how this process is different from diffusion.

6 Consider the images of red blood cells in the following figure. The arrows indicate the direction of net movement of water. Using your understanding of osmosis, explain how red blood cells would:

a shrink

b swell and burst.



7 For which of the following is energy required?

A diffusion
B facilitated diffusion
C osmosis
D active transport

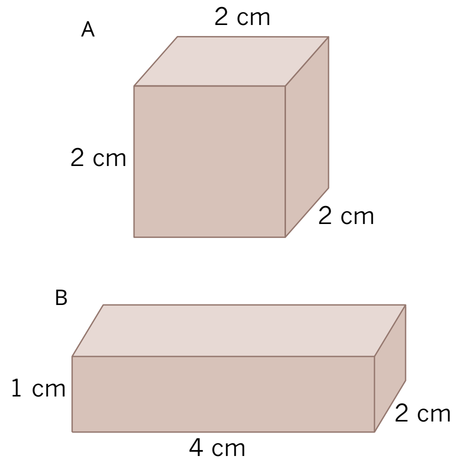
8 **a** Use all the following terms and phrases to write a definition of diffusion: area of low concentration, passive, area of high concentration, concentration gradient, particles, process.

b Explain why diffusion is called a passive process.

c List the factors that affect the rate of diffusion of different types of substances across cell membranes.

9 **a** Explain what is meant by 'surface-area-to-volume ratio'.

b Consider the two objects shown which have the same volume of 8 cm^3. Which shape has the greatest surface area?



3.2 Cell requirements

FIGURE 3.2.1 Sunlight is the primary source of energy for biological systems and the organisms within them.

There is an enormous diversity of living organisms on Earth, but many of their processes and requirements for life are the same. Whether organisms are unicellular or multicellular—and whether they live at the bottom of the ocean or in a rainforest—they all need to take in nutrients and water, exchange gases, obtain energy and remove waste products.

All life on Earth needs a carbon source and other atoms (e.g. oxygen) to build **organic compounds** and an energy source to grow and add mass. Ultimately, most biological systems and organisms rely primarily on one source of energy for their survival: sunlight (Figure 3.2.1). Organisms can be divided into groups according to how they obtain organic compounds and how they obtain energy.

CELL REQUIREMENTS—ENERGY

Organisms can be divided into two groups depending on the strategies they use to obtain organic compounds, which are in turn their source of energy.

- **Autotrophs** (self-feeders) make their own organic compounds from **inorganic compounds** found in the soil and atmosphere. The conversion of inorganic compounds into organic compounds is called **carbon fixation** because the autotroph 'fixes' inorganic carbon into organic molecules, such as glucose. Because autotrophs produce their own nutrients and all of the organic compounds in ecosystems, they are also called **producers**. Autotrophs include all of the green plants that carry out **photosynthesis**.
- **Heterotrophs** (other-feeders) obtain organic compounds by consuming other organisms (autotrophs or other heterotrophs). Because heterotrophs consume (eat) organic compounds, they are also called **consumers**. Heterotrophs include all animals and fungi.

Both autotrophs and heterotrophs use matter (organic and inorganic compounds) to produce the energy required for all biological processes. Photosynthesis and **cellular respiration** are the reactions that cells use to transform matter into energy (Figure 3.2.2). Autotrophs use both photosynthesis and cellular respiration, while heterotrophs use only cellular respiration. The biochemical processes of photosynthesis and cellular respiration are examined in more detail in Section 3.3.

You will learn more about autotrophs and heterotrophs in Chapter 5.

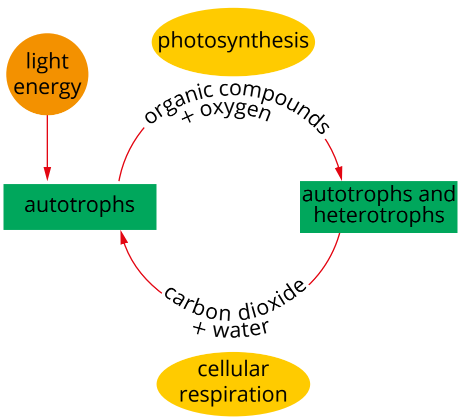


FIGURE 3.2.2 Autotrophic organisms make the organic compounds they require by combining inorganic compounds from their environment during photosynthesis. Heterotrophic organisms obtain the organic compounds they require by eating other organisms or the products of other organisms. Cellular respiration is used by both autotrophs and heterotrophs for the production of energy.

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Compounds are molecules containing atoms of different elements bonded together.

Carbon is a versatile element as a base for organic compounds, because each carbon atom can form bonds with four other atoms. This makes a very large variety of carbon-based molecules possible.

CELL REQUIREMENTS—MATTER

There are 92 different types of naturally occurring atoms on Earth, and each type is known as an element. The same elements that can be found in rocks, soil and air are also found in living cells. But there is a difference in the way that these atoms are organised into larger compounds in living organisms.

Organisms produce characteristic complex compounds that contain carbon and hydrogen (Figure 3.2.3). These are called organic compounds because the first ones discovered were produced by organisms or found in them. Most large organic molecules are composed of many smaller organic molecules linked together. Scientists sometimes refer to this system as a polymer made from monomers. For example, protein molecules are constructed from chains of amino acids, and DNA is made up of a series of nucleotide subunits.

All other compounds, whether in living or non-living things, are called inorganic compounds. Inorganic compounds that are important for living organisms include water, oxygen, carbon dioxide, nitrogen and minerals.

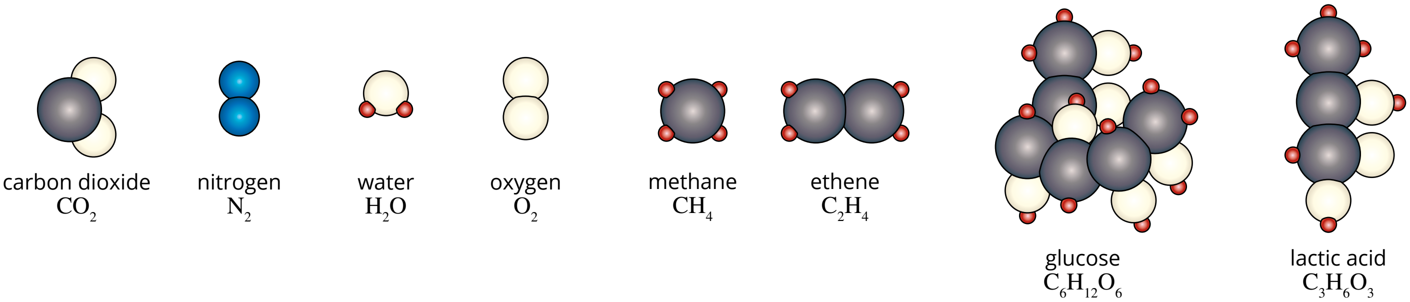

FIGURE 3.2.3 Some common molecules in organisms: carbon dioxide, nitrogen, water, methane, ethene, glucose and lactic acid. These molecules are made up of the atoms carbon (black), oxygen (white), hydrogen (red) and nitrogen (blue). The colours used to represent these atoms are the standard colours used by scientists for molecular models.

Chemical compounds required by living cells include inorganic compounds, organic compounds and structural organic molecules.

Inorganic compounds

Inorganic compounds include water, oxygen, carbon dioxide, nitrogen and minerals.

- **Water** (H_2O) makes up 70–90% of most organisms. It is an important solvent and transport medium. Chemical reactions in cells take place in water-based fluid (cytosol), and some reactions include water.
- **Oxygen** (O_2) is needed for efficient energy supply, achieved by the process of cellular respiration in almost all organisms. It is taken in as a gas by terrestrial organisms and in solution by aquatic organisms.
- **Carbon dioxide** (CO_2) is the ultimate source of the vital carbon atoms for organic molecules, usually starting with carbon fixation by photosynthesis in autotrophs (green plant cells). Carbon dioxide is taken into plant leaves as a gas, converted to sugars and eventually returns to the atmosphere in the carbon cycle.
- **Nitrogen** (N) is a key atom of the 20 types of amino acids that link together to form protein molecules and of the nucleotide subunits that form nucleic acids. Consumers derive their nitrogen atoms from plants, which obtain soluble nitrate ions (NO_3) that are added to the soil by nitrogen-fixing bacteria using N_2 gas from the air. The nitrogen cycle eventually returns N_2 gas to the air.
- **Minerals** are important for building many enzymes and vitamins that are needed for the structure and function of biological systems. Calcium is used for the structural parts of vertebrates, such as bones and teeth. Sodium and potassium are important for nervous system function. Magnesium is important for muscle function, and iron is needed for haemoglobin production in red blood cells. Humans require more than 20 minerals, some in only minute quantities (trace elements).

Organic compounds

Organic compounds include carbohydrates, lipids, proteins and nucleic acids.

- **Carbohydrates** are important energy sources and structural components of organisms. Some important carbohydrates are glucose, sucrose, starch and cellulose. The basic subunits of carbohydrates are simple sugars called **monosaccharides** (single sugars), **disaccharides** (two sugars joined together), and **polysaccharides** (many sugars joined together in long chains) (Figure 3.2.4a). Carbohydrates have hydrogen atoms in a 2:1 ratio with oxygen atoms.
- **Lipids** play an important role in cell membranes. They include fats and oils, which are important for energy storage (Figure 3.2.4b). Lipids are composed of a glycerol 'head' and fatty acid 'tails'. Compared with carbohydrates, lipids contain a much smaller proportion of oxygen, and can contain other elements, such as phosphorus and nitrogen. The role of lipids in cell membranes is covered in detail in Chapter 2.

Organic compounds are the complex chemicals, containing carbon and hydrogen atoms, which are found in living things or have come from living things. This includes proteins, carbohydrates, lipids (fats), vitamins, DNA and RNA. It does not include carbon dioxide, which is a small, simple, inorganic molecule that contains carbon but not hydrogen.

Inorganic compounds are compounds without carbon atoms, or simple molecules with only one or two carbon atoms. Carbon dioxide (CO_2) and methane (CH_4) are considered to be inorganic. Acetic acid (CH_3COOH), methanol (CH_3OH) and glucose ($C_6H_{12}O_6$) are organic because they are more complex, have hydrogen atoms or more than two carbon atoms.

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- **Proteins** are composed of amino acids and have many functions. Some are enzymes, while others are hormones, antibodies or carrier molecules (e.g. haemoglobin). Proteins form part of the cell membrane (Figure 3.2.4c). Organisms have their own unique proteins, unlike the more generic lipids and carbohydrates found in all organisms. As well as carbon, hydrogen and oxygen atoms, proteins always have nitrogen. Their diversity comes from the 20 possible **amino acid** subunits, linked by peptide bonds into **polypeptide** chains, two or more of which are folded into a complex 3D-shaped structure (called the tertiary structure). Proteins are constructed in each cell under coded directions from DNA (genetic information).
- **Nucleic acids** carry the genetic information of cells. The two types of nucleic acids are DNA and RNA, both of which are made of long chains of nucleotides (adenine, guanine, cytosine and thymine in DNA; adenine, guanine, cytosine and uracil in RNA), sugars and phosphates (Figure 3.2.4d). DNA carries the information needed to assemble proteins from amino acid subunits. Genetic information is passed from cell to cell during cell division. RNA plays a major role in the manufacture of proteins within cells.

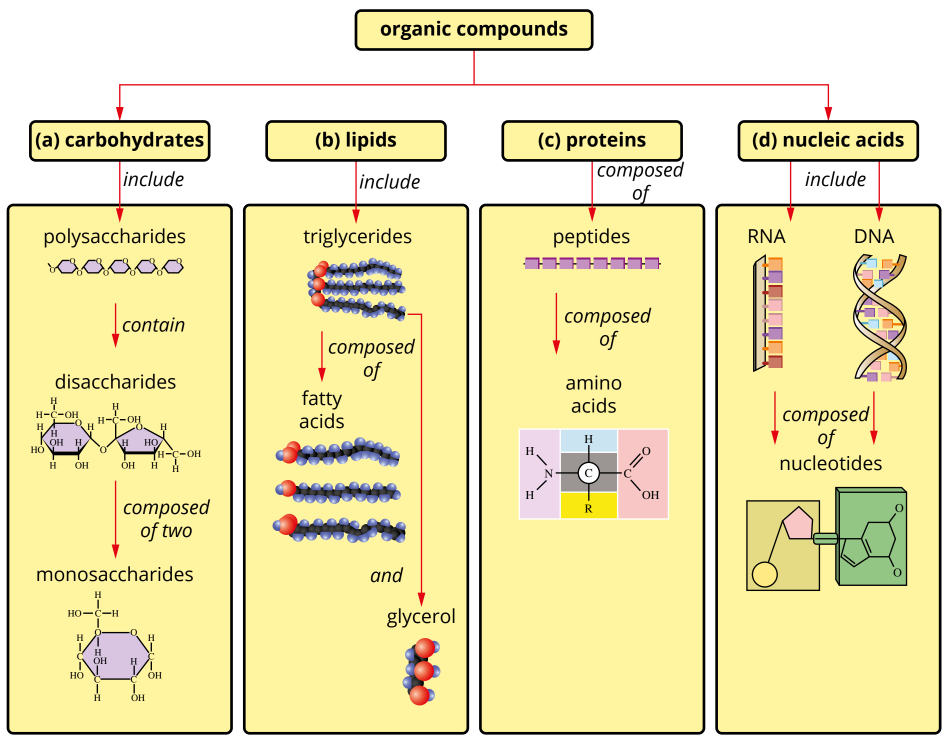

FIGURE 3.2.4 Organic compounds and their components. (a) Carbohydrates are organic compounds of carbon, hydrogen and oxygen and are important energy sources for all cells. (b) Lipids are an important component of cell membranes and play a role in energy storage. (c) Proteins are important for the structure and function of cells and biological systems, and are made up of chains of amino acids called peptides and polypeptides. (d) Nucleic acids are DNA and RNA and contain the genetic instructions for every cell.

Structural organic molecules

Structural organic molecules and **vitamins** are small, organic molecules that are vital for normal cell function (Figure 3.2.5).

- Some organic molecules can be synthesised, but others must be obtained in the diet. For example, most mammals can synthesise vitamin C, but humans must obtain it in their diet. Vitamins may be water soluble (such as vitamins B and C) or lipid soluble (such as vitamins A, D, E and K).
- Water-soluble vitamins must be consumed regularly in the diet because they cannot be stored in body tissues. Lipid-soluble vitamins can be stored. Many vitamins are needed to work with enzymes.

FIGURE 3.2.5 Vitamin food sources and functions in humans

CELL REQUIREMENTS—WASTE REMOVAL

Waste material for one organism may be a useful substance for another. The undigested food (faeces) removed from a vertebrate are useful nutrients for many decomposing bacteria, fungi and protozoa. Operating under strict hygiene conditions, Sydney Water and other wastewater facilities around Australia produce biosolids from activated sludge from sewage. This is the nutrient-rich material created from treating wastewater solids with suitable microorganisms. Biosolids are a rich source of phosphorus and nitrogen and are used in agriculture, horticulture and mining.

The waste products from our digestive system may be the most obvious waste that we think of. However, they are not actually the waste products of cells. They have passed through the digestive tract without actually becoming part of the body—unlike digested food, which has passed into the bloodstream.

As both autotrophic and heterotrophic cells function, they produce substances from their **metabolism** that are no longer useful to them. Accumulation of these waste substances, such as carbon dioxide from cellular respiration and **nitrogenous wastes** from the breakdown of proteins and nucleic acids (DNA and RNA), can prevent cells from functioning properly. The waste substances need to be removed to ensure balance is maintained in the organism. This process is known as **excretion**.

An important property of the cell membrane is to regulate the transport of materials—including any waste material. Depending on the size and concentration of the waste material, transport may be passive or active:

- passive—e.g. osmosis of water molecules; simple diffusion of oxygen, carbon dioxide, ammonia and alcohol; facilitated diffusion of urea, glucose and ions
- active—e.g. urea, toxins and ions being removed against their concentration gradient via endocytosis and exocytosis.

The function of the cell membrane in controlling the movement of materials in and out of the cell is explained in more detail in Section 3.1.

Metabolism refers to the total of all the chemical reactions in a living organism.

Excretion is the removal of substances that once formed part of the body of the organism. It occurs largely in the kidneys. This is different from egestion in mammals, which is the removal of undigested food (faeces) from the gut via the anus.

Waste removal from autotrophs

Autotrophs produce and excrete a variety of waste products, but these are usually considered by-products rather than waste, and elimination may be in subtle ways. Plants (autotrophs) do not require specialised excretory organs, although leaves could be regarded as excreting any carbon dioxide or oxygen gas that is excess to the leaf cell requirements. Compared to heterotrophs, the autotrophic cells produce almost no true waste. This is because they have a much lower **metabolic rate**, can reuse gases such as oxygen and carbon dioxide, and contain fewer protein molecules, thereby producing less nitrogenous waste.

Examples of waste removal in plants include the following.

- For aquatic autotrophs, such as all the algae, e.g. the seaweed *Ulva* (sea lettuce), waste chemicals are passed directly into the surrounding water.
- Some species live in environments where they need to deal with unusual waste problems. One example is the mangrove, which is a tree that lives in the intertidal zone of estuaries (area where saltwater from the ocean meets freshwater from a river). Mangroves are periodically subjected to high levels of salt around their roots. Mangrove adaptations include concentrating excess salt in old leaves and bark, which are then shed; storing salt within enclosed cell vacuoles; and excreting salt crystals onto the leaf surface where they are blown or washed away.
- Some terrestrial (land) plants store wastes in non-living hardwood, or in leaves and bark that are later dropped, such as deciduous trees in autumn, or eucalyptus trees with continuous leaf drop (Figure 3.2.6).

FIGURE 3.2.6 (a) Autumn leaves dropping from deciduous trees carry waste products away. This is more common in the colder countries of the northern hemisphere than in Australia. (b) In Australia, it is common for eucalyptus trees to shed some bark and leaves all year round. This is a way for the tree to eliminate some waste products, such as any toxic chemicals taken up from the soil.

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Waste removal from heterotrophs

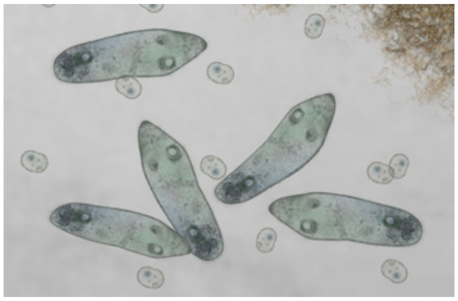

FIGURE 3.2.7 These single-celled *Paramecium* and the smaller *Amoeba* are heterotrophic organisms that live in freshwater. Their small size means they can expel wastes directly into the surrounding water.

Normal metabolic activity for animal (heterotroph) cells is more complex than in autotrophic cells. Heterotrophic cells break down and replace carbohydrates, lipids, nucleic acids (DNA and RNA) and proteins, producing waste products that usually cannot be used by the body.

In unicellular heterotrophs, waste products can be released directly into the surrounding environment. The unicellular organisms *Paramecium* and *Amoeba* are heterotrophic organisms that are common in freshwater (Figure 3.2.7). Their small size means they can expel wastes, including carbon dioxide gas, through their cell membrane directly into the surrounding water. These organisms have structures such as contractile vacuoles, which collect water and wastes internally and periodically pump them out.

More complex heterotrophs require more complex excretory structures and processes. Unlike in plants, the excretory structures of animals are obvious. Animals have specific excretory organs and systems to ensure that wastes are efficiently removed from cells.

Carbon dioxide

FIGURE 3.2.8 Axolotls are a popular aquarium pet that belong to the amphibian group of vertebrates. For gas exchange, including the removal of carbon dioxide, they use gills that extend outwards from their neck.

When carbohydrates or lipids are broken down during cellular respiration to release energy, carbon dioxide and water are produced. These are removed into the surrounding environment by first diffusing across moist respiratory membranes—which in mammals, are in the lungs—and are then breathed out. For aquatic animals, the removal of carbon dioxide may occur by diffusion or via a specialised organ, such as gills (Figures 3.2.8 and 3.2.9). Animal groups that use gills include fish, crustaceans (e.g. crabs, barnacles and krill), some echinoderms (sea stars), aquatic molluscs (shell fish), some amphibians and the larval stage of some insects. Ancient fossils of trilobites show the imprint of gill structures between their many legs.

An efficient removal process is particularly important for carbon dioxide. If it is allowed to build up, it lowers the pH and increases the acidity of the blood and extracellular fluid.

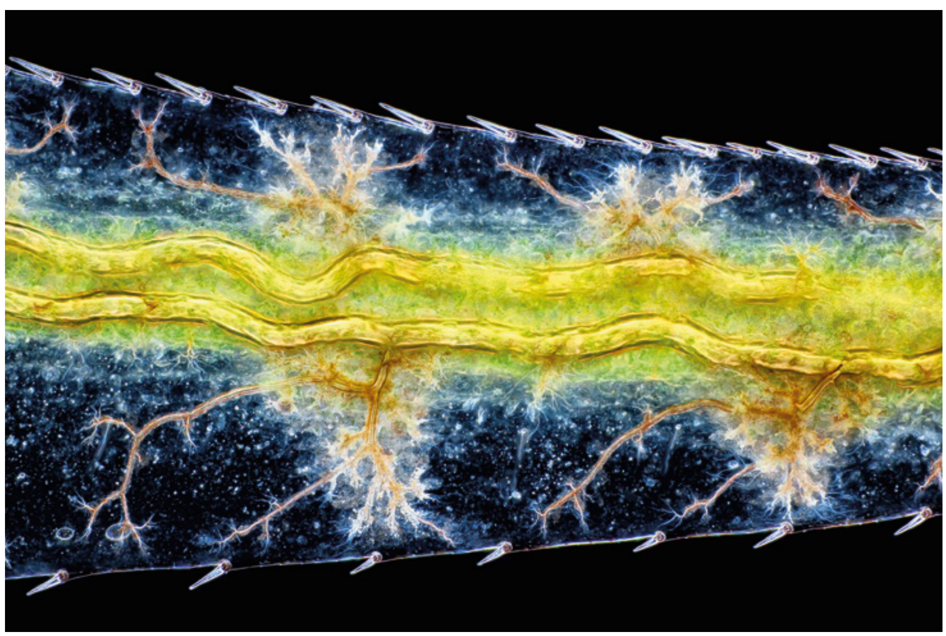

FIGURE 3.2.9 The larval stage of many insects may have gill structures for gas exchange if they live in water. This polarised light microscope image of a damselfly nymph shows fine, branching tubes inside the gill on the nymph's tail end. The tubes facilitate gas exchange in the tissues and reflect the tracheal tubes used for respiration in adult insects.

Water

Water is not usually a waste problem. For terrestrial organisms, water is more likely to be in shortage. If extra water is produced during cellular respiration or by ingestion, it would first be incorporated into normal body fluids. Any excess water is then expelled from the body as water vapour when breathing (Figure 3.2.10) or with urine from the **kidneys** as part of the routine removal of nitrogenous waste. **Urine** can be produced that is more or less diluted as part of the body's **homeostatic** regulatory process. Freshwater animals do have to remove excess water, which is drawn in by osmosis. *Paramecium* (Figure 3.2.7) is an example of an organism that needs to do this.

FIGURE 3.2.10 An American bison breathes out on a winter's day. The water vapour in its breath becomes obvious as it condenses from gas to liquid droplets in the very cold air.

Nitrogenous wastes

Proteins are made up of amino acid molecules, which all contain nitrogen atoms (N) as part of their structure. When proteins are broken down, the nitrogenous parts are split off and the remainder of the molecule is converted into carbohydrates or lipids, which can be used for energy. The remaining nitrogenous waste must be removed from the cell, because it can become toxic. Cells also break down and recycle nucleic acids (DNA and RNA), releasing yet more nitrogenous waste. Multicellular animals use their circulatory systems to transport wastes away from cells to the excretory organs.

In mammals, nitrogenous waste is first managed by the liver, and then regulated by the kidneys and excreted as urea in the urine. Specialised structures called nephrons in the kidneys regulate the concentration of water and soluble substances in the body by filtering the blood (Figure 3.2.11). Close interactions between blood vessels and each nephron ensure that the blood is continuously filtered to remove urea and form urine, yet retains useful substances. During the filtration process, other toxins are also removed from the blood and the salt–water balance of the body is maintained.

The biochemical management of nitrogenous waste will be explained in more detail in Section 3.3.

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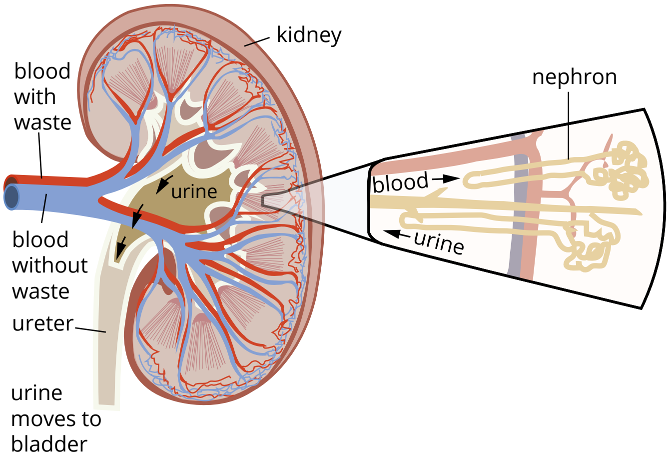

FIGURE 3.2.11 There are about one million functioning nephron units in each human kidney. The nephrons filter the blood and remove waste products from the body as urine.

3.2 Review

SUMMARY

- Autotrophs use energy and inorganic molecules from their environment to produce the organic compounds they need in a process called carbon fixation.
- Most autotrophs, including plants and algae, are photosynthetic. They use solar energy and inorganic molecules for producing energy-rich organic compounds (usually glucose).
- Heterotrophs—including animals, fungi and some bacteria and protists—obtain organic compounds by eating other organisms or their products.
- Inorganic components of living organisms include water, oxygen, carbon dioxide, nitrogen and minerals.
- Organic components include carbohydrates, lipids, proteins, nucleic acids and vitamins.
- Carbon dioxide is the ultimate source of carbon for organic molecules, and nitrogen is a key molecule of proteins.
- Carbohydrates are important as energy sources and for structural components of organisms.
- Lipids play an important role in cell membranes.
- Proteins play many important roles in the structure and function of biological systems. Proteins are made up of chains of amino acids. Organisms have their own unique proteins, including the many enzymes needed for metabolism.
- Nucleic acids (DNA and RNA) carry the genetic information of cells. The genetic information of a cell provides all the instructions for the growth, function and reproduction of cells and organisms.
- Excretion is the removal of substances that once formed part of the body of the organism and are now treated as waste.
- Autotrophs and heterotrophs (animals) differ significantly in their formation and elimination of waste products.
- Heterotrophs, especially those living on land, have complex systems and organs to excrete wastes with minimal loss of water.
- Removal of waste or excess products is essential to maintain a healthy balance in the body of any organism.
- As the organism carries out its metabolic functions, the concentrations of useful and harmful substances will vary.
- In animals, carbon dioxide is removed by the circulatory and respiratory systems working together.
- In animals, nitrogenous wastes are removed by the circulatory and excretory systems working together.

KEY QUESTIONS

1 Why are autotrophs also called producers?

2 a Define the terms 'organic compound' and 'inorganic compound'.

b Is carbon dioxide organic or inorganic? Explain.

3 Which of the following statements is true?

A All organic compounds contain carbon and nitrogen.

B All organic compounds contain carbon and hydrogen.

C All organic compounds contain carbon, hydrogen and oxygen.

D All organic compounds contain carbon and oxygen.

4 Identify the source of each of these wastes and explain why they need to be removed from heterotrophs.

a carbon dioxide

b nitrogenous waste

5 Match each of the following terms to the correct statement.

carbohydrate	by-product of cellular respiration
carbon dioxide	composed of amino acids
lipid	compound of carbon, hydrogen and oxygen
mineral	examples are phosphorus, calcium and potassium
nucleic acid	fatty substance stored in tissues
oxygen	made of subunits called nucleotides
protein	may be water soluble or lipid soluble
vitamin	needed for cellular respiration

6 State two reasons why autotrophs have fewer waste products than heterotrophs.

7 Identify the main waste products produced by heterotrophic cells and explain how they are removed.

3.3 Biochemical processes in cells

Living things can be divided into autotrophs—those that can produce their own organic materials—and heterotrophs, which must consume the organic materials produced by others. The cells of both types of organism use the biochemical process of cellular respiration to obtain energy from glucose to carry out cellular activities (Figure 3.3.1). Only in autotrophs do cells use solar energy to power part of the biochemical pathway, known as photosynthesis, and produce their own organic material. During metabolic processes like these, cells produce some waste or excess substances that need to be removed to maintain a stable internal environment.

Metabolic reactions are all the chemical reactions involving matter and energy in a living organism. Each reaction is controlled by an enzyme.

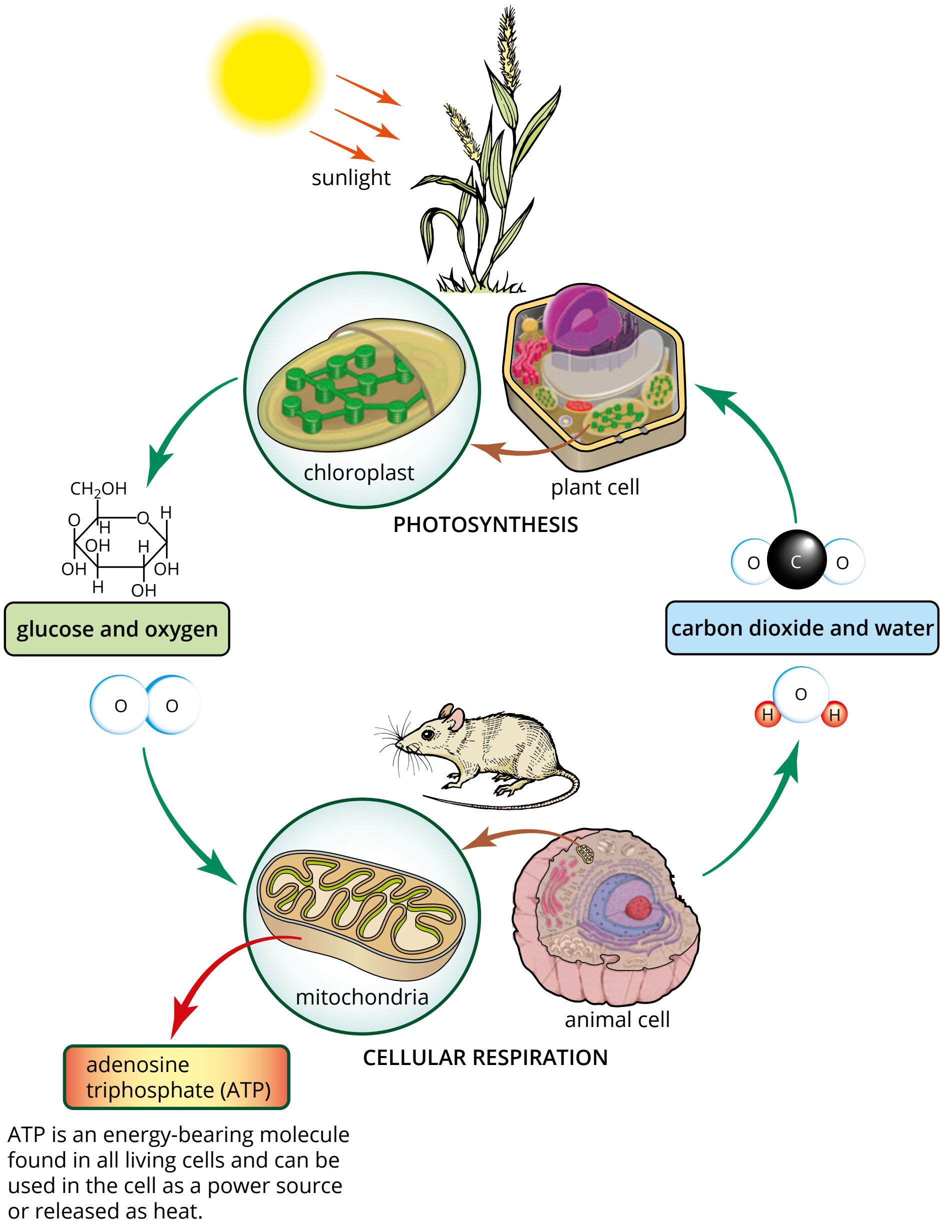

FIGURE 3.3.1 This cycle shows how plants obtain their energy using photosynthesis and cellular respiration. Animals obtain their energy via cellular respiration.

PHOTOSYNTHESIS IN EUKARYOTIC CELLS

Plants produce glucose by a **biochemical** process called photosynthesis. Photosynthesis is the process in which plants and other photoautotrophic organisms obtain energy from sunlight to make their own organic compounds. This section will focus on photosynthesis in eukaryotic cells.

Simple experiments show that when plants have light, water (H_2O) and carbon dioxide (CO_2), they make glucose ($C_6H_{12}O_6$) in their green tissues, usually the leaves (Figure 3.3.2). They trap the energy from sunlight and convert it into chemical energy, which they store in the bonds of glucose molecules. This enzyme-controlled process is photosynthesis ('*photo*' meaning 'light', '*synthesis*' meaning 'putting together').

All photosynthetic organisms, from single-celled algae to the largest trees, produce glucose in the same way (Figure 3.3.1). The ability to carry out photosynthesis means that green plants are classed as autotrophs.

Photosynthesis is sometimes called carbon fixation. This is because carbon atoms from the carbon dioxide gas in the air are incorporated (fixed) into organic molecules, such as glucose.

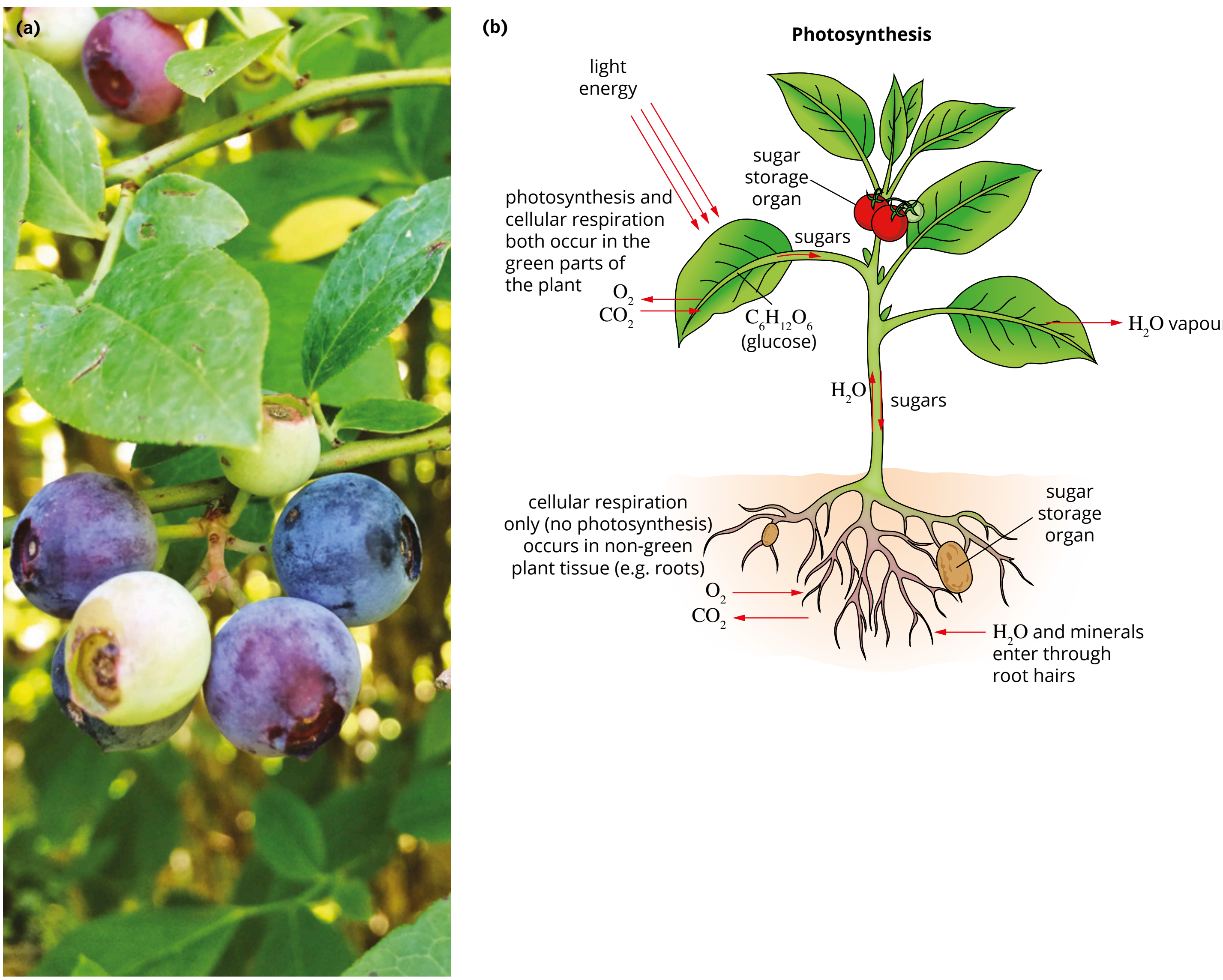

FIGURE 3.3.2 Photosynthesis only occurs in the green parts of a plant. (a) The leaves and some stems of plants look green because many of their cells contain chloroplasts, which are full of the green pigment called chlorophyll. Chloroplasts are the organelles in which photosynthesis takes place. Fruits, such as these blueberries, do not take part in photosynthesis. (b) Fruits, flowers, roots and seeds contain no chlorophyll and do not take part in photosynthesis. They have other functions, some of which support photosynthesis.

BIOLOGY IN ACTION CCT WE

Investigating photosynthesis

Photosynthesis can be detected in several ways in a school laboratory. Some of these methods provide qualitative data, while others provide quantitative data. A few examples of materials you might use to conduct an investigation are described here.

Photosynthesis can be studied in plants, growing seedlings, algae and cyanobacteria. In water, the rate of photosynthesis in plants and algae can be estimated by measuring oxygen production. To measure oxygen levels, a device called a photosynthometer is used. The photosynthometer is a syringe connected by tubing to pond water surrounding a water plant, such as *Elodea*. Oxygen is collected and measured in the syringe (Figure 3.3.3a).

Another approach is to measure the change in pH of the water; for example, by using a hydrogen carbonate pH indicator (Figure 3.3.3b). Algae are immobilised in small alginate balls in each tube and the pH change is measured. As carbon dioxide is removed from the water for use during photosynthesis, the pH of the water will increase (become more alkaline).

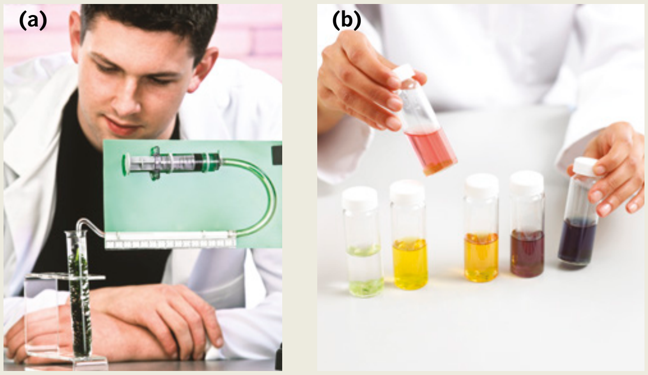

FIGURE 3.3.3 Students investigate photosynthesis by different methods. (a) Measuring oxygen produced by pond weed (in the test tube). As the pond weed photosynthesises, it produces oxygen, which is collected and the volume measured in the photosynthometer (syringe connected by tubing to pond water). (b) Measuring pH change with hydrogen carbonate indicator. Algae are immobilised in small alginate balls in each tube, and the pH change reflects carbon dioxide intake for photosynthesis.

Photosynthesis can also be investigated in small leaf discs. The discs trap oxygen gas as they photosynthesise, become buoyant and float. Conditions that may affect the rate of photosynthesis, such as light intensity, temperature and chlorophyll concentration, can be investigated using these methods.

Chloroplasts

Chloroplasts are the sites of photosynthesis—where light energy is converted to food (glucose) for the plant and where oxygen is released. The function of these important organelles sustains almost all life on Earth. Chloroplasts are found in the cells of the leaves and green stems of **vascular plants**, and throughout the leaves of non-vascular plants, such as mosses. The leaves, and sometimes stems, of plants are green because of the green pigment **chlorophyll** that is inside chloroplasts. The chlorophyll molecules absorb energy from sunlight, the essential first stage of photosynthesis.

In vascular plants, chloroplasts are found in **mesophyll** cells, which make up the upper surface of leaves (Figure 3.3.4). The mesophyll cells are packed with chloroplasts and are the main sites of photosynthesis. The location of mesophyll cells near the upper surface of the leaf means that the chloroplasts have maximum exposure to sunlight, increasing the rate of photosynthesis.

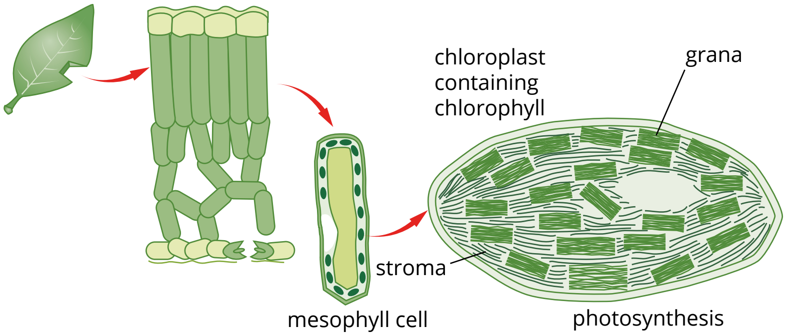

FIGURE 3.3.4 The location of mesophyll cells and chloroplasts in the leaf of a vascular plant. The mesophyll cells make up the upper layer of the leaf, which is the part of the plant that is most exposed to sunlight.

In plants and algae, the chloroplasts are surrounded by a double membrane. Inside each chloroplast are stacks of flattened membranes called **grana** (singular granum) (Figures 3.3.4 and 3.3.5).

Photosynthesis takes place inside the chloroplasts, which are numerous in each mesophyll cell. The grana stacks contain the chlorophyll pigments where reactions using light energy occur during photosynthesis.

Plant chloroplasts are generally shaped like a biconvex lens about 5–8 μm in diameter. The outer membrane is highly permeable. The inner membrane is impermeable and surrounds the area filled with a liquid called **stroma**. Stroma contains a number of enzymes, spherical DNA and ribosomes. The grana hold stacks of small disc-shaped structures called **thylakoids** where chlorophyll is made (Figure 3.3.5).

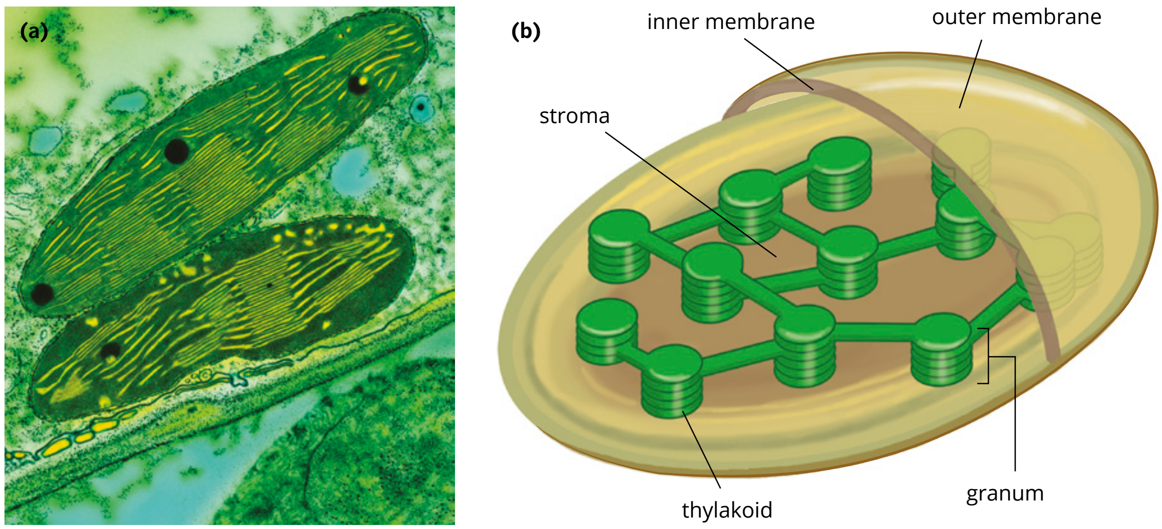

FIGURE 3.3.5 (a) TEM image of two chloroplasts in a cell in the leaf of a pea plant (*Pisum sativum*). The chloroplasts are seen here in side view, and the grana are coloured yellow. (b) Three-dimensional model of the structure of a chloroplast

Photosynthesis in non-green plants, protists and cyanobacteria

All plants (as well as many protists and cyanobacteria) contain chlorophyll, but not all are green. Some plants have yellow, red or purple leaves, and protists and cyanobacteria can be red, blue or other colours (Figure 3.3.6). These organisms do contain chlorophyll, but also have other pigments, including phycobiliproteins and carotenoids, which mask the green chlorophyll.

FIGURE 3.3.6 This oxalis plant (*Oxalis triangularis*) has purple leaves, but these still contain chloroplasts and chlorophyll and carry out photosynthesis.

Phycobiliproteins and carotenoids assist in photosynthesis by absorbing different wavelengths of light. Phycobiliproteins are especially useful in deep water, where only green wavelengths can penetrate. Pigments other than chlorophyll also protect plants from overexposure to sunlight and attract pollinators. There are six known types of chlorophyll, with chlorophyll-a being the most prevalent.

Stages of photosynthesis

Photosynthesis is often simplified into an equation such as the one shown in Figure 3.3.7. In reality, it is a complex biochemical process in which solar energy is converted into chemical energy stored in the form of glucose, which can be used by all organisms. Photosynthesis occurs in a series of chemical reactions spread over two stages: the **light-dependent reactions** and the **light-independent reactions**. In Section 3.4 you will learn how the pathway is controlled by enzymes.

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Stage 1: Light-dependent reactions

In the light-dependent reactions, chlorophyll captures solar energy and uses it to produce **adenosine triphosphate (ATP)**. During this process, **photolysis** occurs, where water is split into hydrogen ions and oxygen gas. The light-dependent reactions occur on the thylakoid membranes (grana) of the chloroplast, where chlorophyll molecules are located.

The light-dependent reactions split water in the presence of solar energy (light) and chlorophyll, into hydrogen ions and molecular oxygen, and also produce ATP.

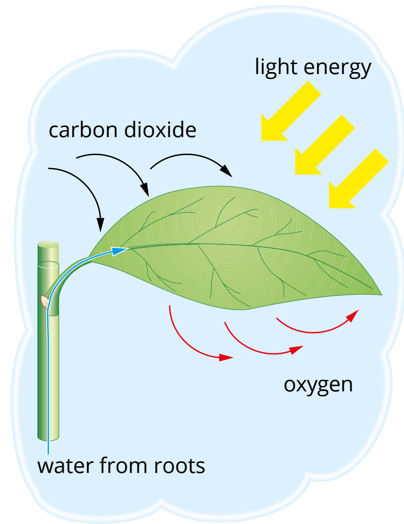
$$\text{water} \xrightarrow[\text{chlorophyll}]{\text{light energy}} \text{hydrogen ions} + \text{oxygen} + \text{ATP}$$

Stage 2: Light-independent reactions

The light-independent reactions (also called dark reactions) produce glucose, water and **adenosine diphosphate (ADP)**. These reactions are called light-independent because they do not require solar energy. ATP made during Stage 1, the light-dependent stage, provides the energy for the dark reactions. This energy is needed to combine carbon dioxide with hydrogen ions (also from the light-dependent stage) to form glucose—an energy-rich, organic molecule—and water. The light-independent reactions take place in the stroma (fluid part) of the chloroplast.

The light-independent (or dark) reactions use the products of the light-dependent reactions to produce glucose, water and ADP.

$$\text{hydrogen ions} + \text{ATP} + \text{carbon dioxide} \rightarrow \text{glucose} + \text{water} + \text{ADP}$$



$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{light energy}} C_6H_{12}O_6 + 6O_2$$

FIGURE 3.3.7 A simplified representation of photosynthesis

Photosynthesis is critically important for life on Earth. This is because carbon fixation and the production of plant matter is essential in providing energy and biomass in both aquatic and terrestrial ecosystems. Plants can produce all the organic compounds they need from the glucose they produce by photosynthesis, as long as they have the necessary minerals (Figure 3.3.8).

Biomass is the total amount of plant and animal tissues in a defined area.

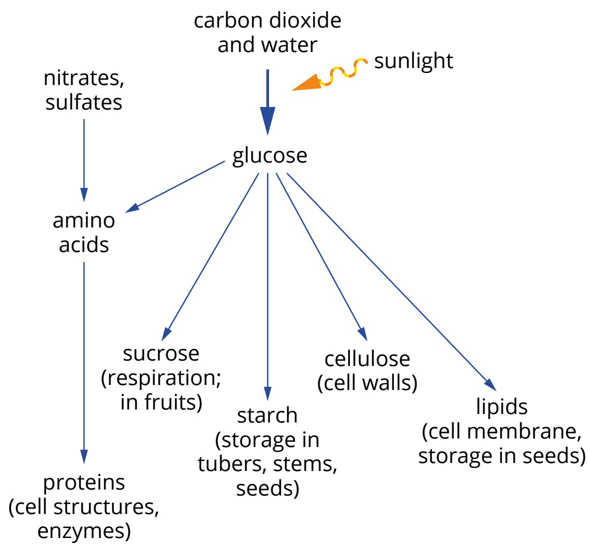


FIGURE 3.3.8 Plants can make all the organic compounds they need from the glucose they produce through photosynthesis.

The reactions that occur in photosynthesis can be summarised as follows:

Word equation: $\text{water} + \text{carbon dioxide} \xrightarrow[\text{chlorophyll}]{\text{light energy}} \text{glucose} + \text{oxygen}$

Chemical equation: $6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$

BIOFILE S

Biofuels

In some places, such as the artificial ponds in France shown in Figure 3.3.9, algae are being cultured to compost household waste. The process releases methane gas, which is burnt to produce electricity. Carbon dioxide is captured from burning of combustible rubbish and provided to the algae (*Chlorella vulgaris*) to sustain their photosynthesis.

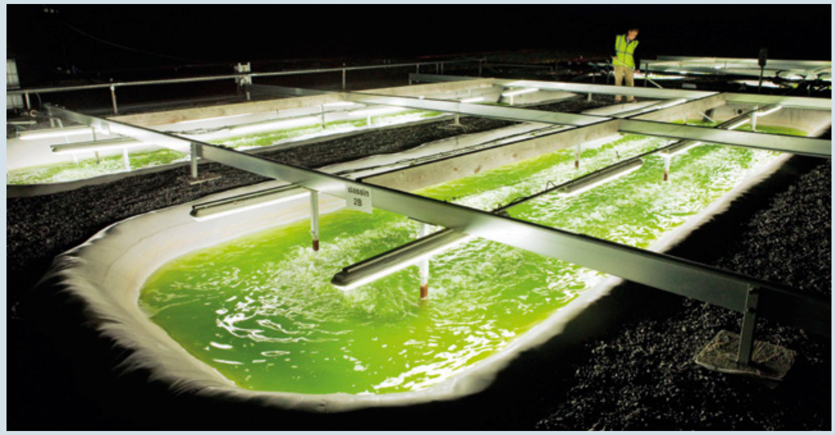


FIGURE 3.3.9 Aquaculture ponds of microalgae produce biofuels from household wastes in a sustainable system.

BIOLOGY IN ACTION ICT S

Bionic leaf and bacteria make liquid fuel

Scientists from Harvard University have created a system that uses bacteria and solar energy to manufacture a liquid fuel from water and carbon dioxide. The researchers set out to develop a renewable energy production system that would mimic the process of photosynthesis, but also be more efficient. They achieved this by creating a structure known as the Bionic Leaf and pairing it with bacteria that use hydrogen and carbon dioxide as their energy sources.

The Bionic Leaf uses electricity generated by a solar panel to split water into its component elements (hydrogen and oxygen) by photolysis, just as photosynthesis does. The electrodes of the Bionic Leaf are submerged in a vial containing water and the soil bacterium *Ralstonia eutropha* (Figure 3.3.10). The water-splitting reaction occurs when an electric voltage from the solar panels is applied to the electrodes of the artificial leaf. The bacteria feed on the hydrogen generated from the reaction, along with carbon dioxide bubbles that are added to the system. The bacteria use this food source and produce isopropanol as a by-product.

This system can now convert water and carbon dioxide to fuel at an efficiency of 3.2%, which is triple the efficiency of photosynthesis. This efficiency is thanks to the solar panels, which have a greater capacity to harvest sunlight than do most plants.

The researchers' findings were published in 2015 and have great potential for use in many powerful applications. Efficient renewable energy production and storage is one of the important areas where this technology could be applied.

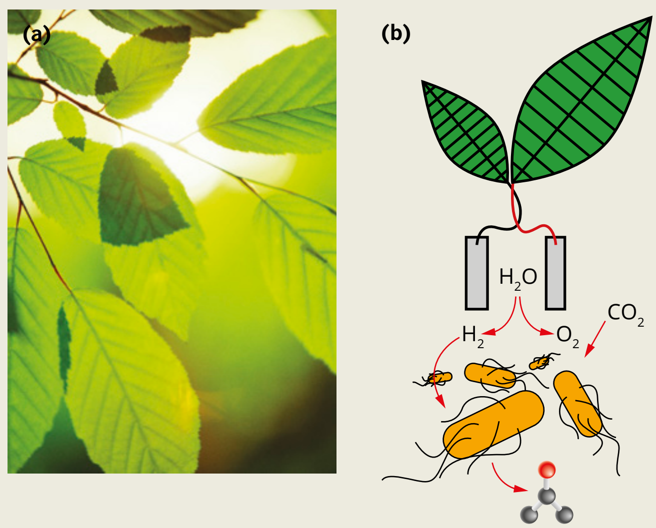


FIGURE 3.3.10 The Bionic Leaf is a renewable energy production system that mimics the natural process of photosynthesis (a). Using electricity harnessed from sunlight, the Bionic Leaf splits water into hydrogen and oxygen (b). Bacteria feed on hydrogen that is produced from this reaction and produce an alcohol called isopropanol as a waste product. The isopropanol can be used as a liquid fuel.

Genetic engineering of bacteria also creates many possibilities for the synthesis and metabolism of a wide variety of chemicals. This might create countless applications for the technology, in both the production of compounds and the removal of chemical pollutants from the environment.

Controlling the rate of photosynthesis

Three main factors control the rate of photosynthesis:

- light intensity
- carbon dioxide concentration
- temperature.

The availability or concentrations of these factors may limit the rate of the reactions in the photosynthesis pathway. For each factor, there is an optimum amount at which photosynthetic reactions proceed at the fastest rate. Below the optimum level, reactions are slower. At levels above the optimum, reactions do not proceed any faster—and sometimes occur more slowly.

The factor that is present in the smallest amount is the **limiting factor**. Therefore, only one factor will be limiting at a particular time. For example, if a plant is in the process of photosynthesis and there is a large amount of carbon dioxide available but not enough light, then light is a limiting factor. And if there is enough light and not enough carbon dioxide, then the concentration of carbon dioxide is the limiting factor (Figure 3.3.11).

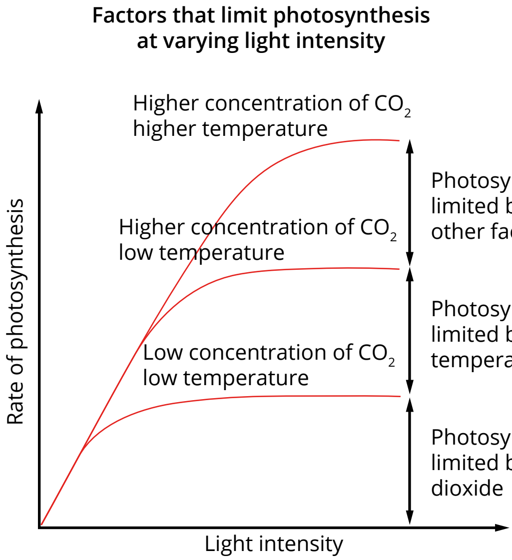


FIGURE 3.3.11 Light intensity, temperature and carbon dioxide are limiting factors for photosynthesis. The factor that is present in the smallest amount is the limiting factor.

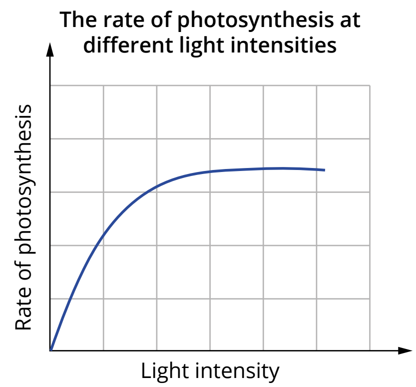


FIGURE 3.3.12 The effect of light intensity on the rate of photosynthesis

Light intensity

Light intensity can affect the rate of photosynthesis. When light intensity is low, the light-dependent reactions in the grana of the chloroplasts (the production of ATP and the splitting of water molecules by photolysis) cannot occur. So at night, light intensity is the limiting factor, because photosynthesis cannot occur.

As light intensity increases from this point, the rate of photosynthesis will increase. However, at a certain light intensity, the rate of photosynthesis will not be affected by further increases in light intensity. This effect can be seen in Figure 3.3.12.

Plants living in shaded environments have adaptations to enable them to photosynthesise under low light conditions (Figure 3.3.13). They have low respiration rates, fewer cells per leaf and lower concentrations of proteins compared with species that grow in sunnier places. In terms of energy requirements, they can be thought of as very cheap to run. Shade-tolerant plants also absorb light very effectively. Some plants that grow in dark environments have a lens-like arrangement in the upper epidermal cells that focuses light onto their photosynthetic cells below.

FIGURE 3.3.13 Most ferns, such as this maidenhair fern (*Adiantum pedatum*), are adapted to thrive in shady environments.

Carbon dioxide levels

Carbon dioxide availability affects the rate of photosynthesis because photosynthesis uses the carbon atoms from carbon dioxide to make glucose. When no carbon dioxide is available, photosynthesis cannot occur, so carbon dioxide is a limiting factor. As carbon dioxide becomes available, photosynthesis begins. As with light, the rate of photosynthesis will increase as carbon dioxide levels increase until the carbon dioxide levels reach a certain point when the reaction rate will plateau (Figure 3.3.14).

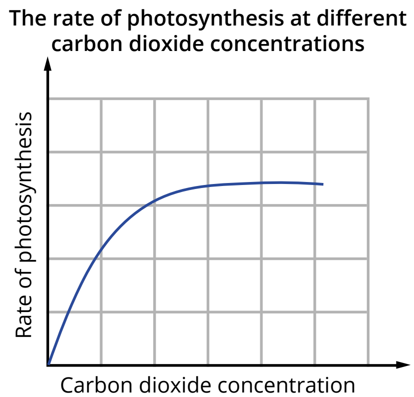


FIGURE 3.3.14 The effect of carbon dioxide levels on the rate of photosynthesis

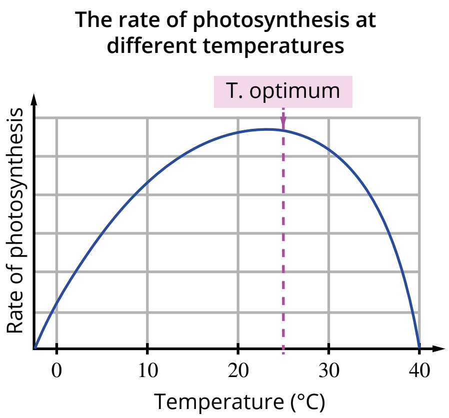


FIGURE 3.3.15 The effect of temperature on the rate of photosynthesis. Notice the steep decline when temperatures are higher than the optimum (T. optimum), unlike the limiting factors of light and carbon dioxide, where the graphs show a plateau effect.

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Temperature

Temperature also affects the rate of photosynthesis. All light-dependent and light-independent reactions are catalysed by enzymes. Enzyme activity initially increases as temperature increases, but enzyme molecules become **denatured** above optimum temperatures, and can no longer function. For this reason, the rate of photosynthesis will approximately double for every increase in temperature until the optimum temperature is reached. Above the optimum temperature, the rate of photosynthesis will not stay level. It will decline steeply as the enzymes become denatured and the chemical processes involved in the light-independent reactions cannot be catalysed (see Figure 3.3.15). Different plants are adapted to different environments; hence, there is no fixed optimum temperature for plant enzymes. The enzymes in a cactus will have a higher optimum temperature than those in an aquatic plant in cool water. Plant enzymes are described further in Section 3.4.

Balancing photosynthesis and cellular respiration

Cells release chemical energy by breaking apart glucose molecules. This process is called cellular respiration. As well as producing energy in the form of ATP, cellular respiration produces carbon dioxide and water.

For plants, cellular respiration occurs continuously, whereas photosynthesis occurs only during daylight. So although plants and algae produce carbon dioxide and use oxygen continuously through cellular respiration, this is masked during the day because photosynthesis is also occurring, using carbon dioxide and producing oxygen.

At low levels of light intensity, the rate of cellular respiration is greater than the rate of photosynthesis. This means there is a net uptake of oxygen by plants. At high light levels, the rate of photosynthesis is greater than the rate of cellular respiration, so there is a net output of oxygen by plants. The **light compensation point** is the level of light at which the rates of photosynthesis and cellular respiration of a photosynthetic organism are equal and there is no net exchange of oxygen (Figure 3.3.16). At this point, the amount of oxygen used in cellular respiration and the amount produced by photosynthesis are equal.

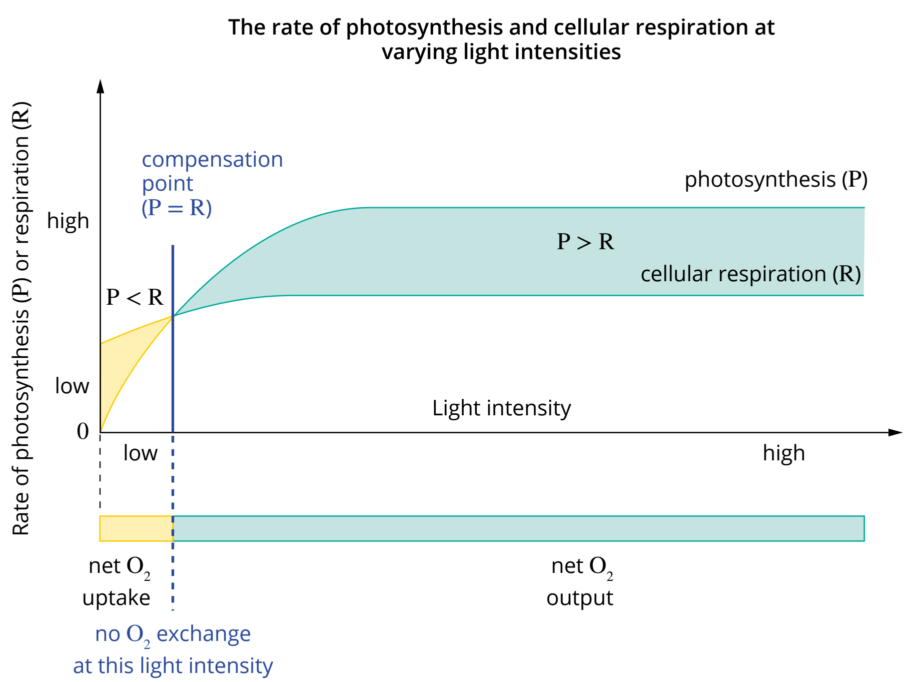

FIGURE 3.3.16 The rate of cellular respiration is greater than the rate of photosynthesis in low levels of light intensity, so there is a net uptake of oxygen by plants. When the rate of photosynthesis is greater than the rate of cellular respiration in high levels of light, there is a net output of oxygen by plants. The compensation point is the level of light at which the rates of cellular respiration and photosynthesis are equal. At this point, there is no net exchange of oxygen.

CELLULAR RESPIRATION IN EUKARYOTIC CELLS

Cells need energy to do work—and in mammals and birds, to also generate body heat. The energy used by organisms and their cells is stored in the chemical bonds of organic compounds. There are different ways that organisms acquire energy in this form.

Energy cannot be created or destroyed—but it can be changed from one form into another. Cells obtain energy from organic compounds, such as glucose. They transform the chemical energy stored in organic compounds into a more usable form of chemical energy, which is stored in the bonds of ATP. This transformation of energy occurs by a biochemical process called cellular respiration (Figure 3.3.17).

The biochemical pathway of cellular respiration varies according to the availability of free oxygen. It also depends on the availability of a basic carbohydrate—the glucose molecule. Animals (heterotrophs) obtain their glucose by eating other organisms and breaking down the organic molecules. Plants (autotrophs) make their own glucose from raw materials.

Cellular respiration is important not only for cells, but on a much larger scale. A healthy ecosystem works by the interconnection and balance of cellular respiration and photosynthesis. These biochemical processes in plant and animal cells are part of the carbon and oxygen cycles that sustain life.

Cellular respiration is a chemical reaction that occurs in living cells. It uses glucose and oxygen to produce usable energy, with carbon dioxide formed as waste. The term ‘respiration’ is used for vertebrates when they exchange gases with the air, breathing out carbon dioxide and taking in oxygen.

Although cellular respiration sometimes refers to both aerobic and anaerobic processes, here it refers only to the aerobic pathways of energy release that occur in mitochondria in eukaryotic cells.

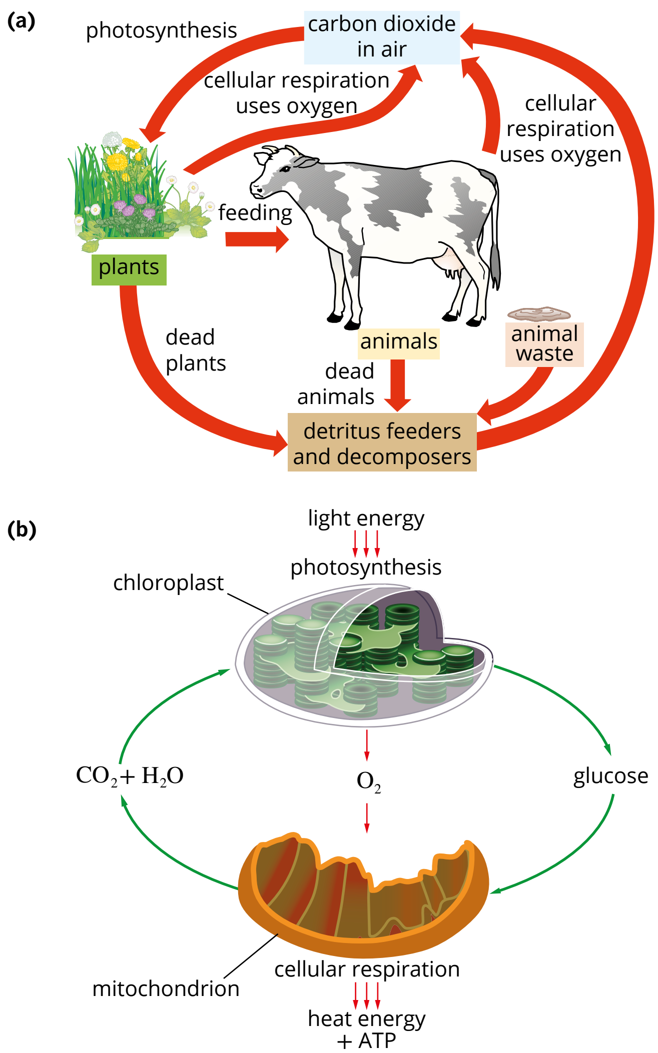

FIGURE 3.3.17 (a) Cellular respiration and photosynthesis operate together as part of the carbon and oxygen cycles in an ecosystem. (b) The cycling of materials is driven by biochemical processes in the two cell organelles, chloroplasts and mitochondria, using energy derived from sunlight.

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Exercise and energy use

When cells convert energy from one form to another, some energy is always lost to the surroundings, usually as heat. For example, during exercise, you use ATP to make your muscles contract (Figure 3.3.18). The more work you do, the more energy you use. When energy use increases, so does the loss of energy as heat, which warms your muscles. This continual generation of heat energy allows mammals and birds to maintain a stable body temperature when their surroundings are colder. Working muscles regularly also improves blood circulation, strength and general health.

FIGURE 3.3.18 This woman is using energy to lift the weights. Her muscle cells are using ATP to do this work, which in turn warms her muscles as some of the energy is lost as heat.

Cells need energy to do work

All living cells require energy to carry out their functions. Energy can be defined as the ability to cause change. For example, you are using energy right now to move your eyes to read these words, just as the cells inside your body are currently using energy to transport substances across their membranes. You, like all organisms, are constantly expending energy.

Energy exists in many forms. The energy in sunlight is solar energy. The heat generated by your body is thermal energy. When you turn a page, the movement involves kinetic (movement) energy. Chemical energy is the potential energy that can be released by a chemical reaction. Chemical energy is stored in the bonds or connections that join atoms together; for example, between atoms of carbon and hydrogen in organic compounds, such as glucose, fats and proteins. The cells of all organisms use the energy stored in these organic compounds.

When energy is required by a cell, the bonds of organic compounds are broken and energy is released and stored in ATP molecules where it is readily accessible.

ATP (adenosine triphosphate)

ATP is the universal carrier of energy in living organisms. Molecules of ATP are the cell's store of immediately usable chemical energy that is required for cell processes. They can be compared to a charged battery that releases energy when required and can be easily recharged.

The ATP molecule contains two high-energy bonds between the inorganic phosphate groups (Figure 3.3.19). These bonds can be easily broken to release a small 'packet' of energy. These packets of energy are used to carry out all the energy-dependent processes of cells. How many are used at once depends on how much energy is required.

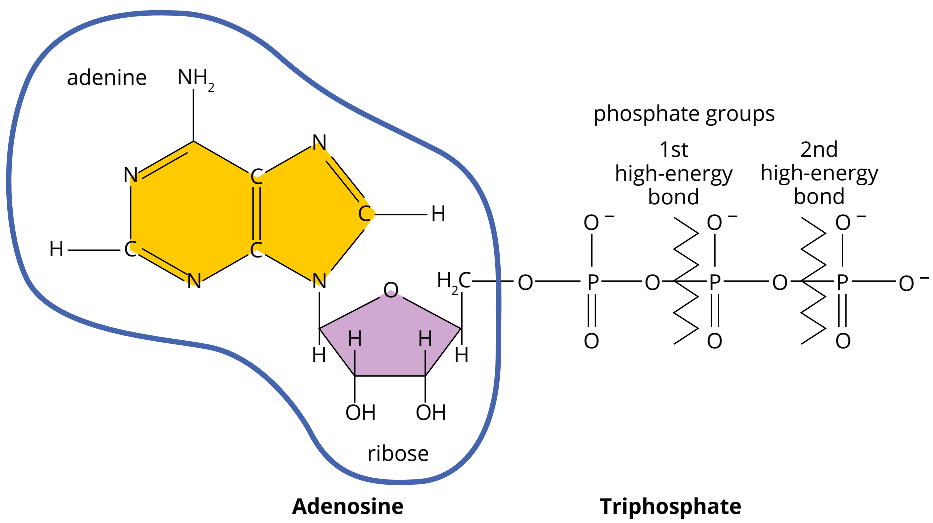

FIGURE 3.3.19 The adenosine triphosphate (ATP) molecule contains the sugar ribose, the nitrogenous base adenine (together creating adenosine) and a chain of three phosphate groups (triphosphate).

When an ATP molecule gives up its energy, it splits into a molecule of ADP (adenosine diphosphate) and a phosphate ion. This process is reversible, because the ADP can readily combine back with a phosphate ion to form an ATP molecule again, using energy derived from the breakdown of glucose during cellular respiration (Figure 3.3.20). The recycling process requires much less energy than it would take to make an entirely new ATP molecule. It is like recharging an existing battery, rather than buying a new one.

Cells obtain most of their energy for making ATP by breaking apart glucose, lipids and proteins. Glucose is one of the energy-rich products of photosynthesis (Figure 3.3.17).

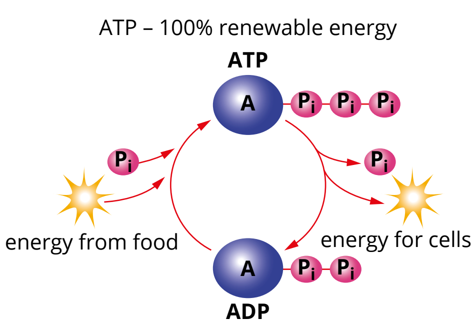

FIGURE 3.3.20 All living cells rely on one source of energy to do everything from building molecules to flexing muscles. This source of energy is adenosine triphosphate (ATP). Enzymes control the synthesis and breakdown of ATP. P_i represents inorganic phosphate, which is a free phosphate ion.

The chemical energy from the glucose molecule is released in a series of steps that involve many enzymes producing many packets of energy as described above. Each energy packet can be used to produce an ATP molecule from ADP and a phosphate ion.

The substance added to ADP to form ATP is phosphate (PO_4). This can be abbreviated to P_i, which stands for inorganic phosphate.

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Other energy molecules

Glucose is the molecule most commonly used as the source of energy in cells. However, cells can also release chemical energy from other organic compounds, such as fats and proteins, to make ATP.

In animals, if most of the available glucose stores are gone (such as during times of food shortage or extreme prolonged activity), fat stores are used to provide the ATP needed for cells to continue functioning (Figure 3.3.21).

In extreme cases, such as during long periods of starvation, even the proteins in muscles and other body tissues will be broken down to provide the energy necessary to survive. Fats provide more energy per gram (39 kJ) than carbohydrates or proteins (17 kJ), but the conversion process is slower and more complex.

FIGURE 3.3.21 (a) The cells of this underweight horse have converted stores of fat into ATP to help the horse survive. (b) Rebecca Clarke of New Zealand shows the exhaustion of completing a triathlon at the World Championship in Stockholm. During the race, her glucose and oxygen levels would have been severely depleted.

Biochemical pathway for cellular respiration

The breakdown of glucose molecules (Figure 3.3.22) results in three products:

- carbon dioxide
- water
- energy.

Of the chemical energy released in the breakdown of glucose, almost 40% is converted to energy stored in the bonds of ATP molecules during aerobic respiration. The rest is lost as heat.

Cellular respiration can be divided into two main stages:

- **Glycolysis** is the first stage, which splits glucose molecules into two parts and does not require oxygen.
- **Aerobic respiration** (if oxygen is present) or **anaerobic respiration** (if oxygen is absent; also called fermentation) is the second stage. In a living cell, anaerobic respiration occurs if insufficient oxygen is available, but aerobic respiration happens at the same time, using all the available oxygen. The total amount of energy that can be harvested depends on whether or not oxygen is present.

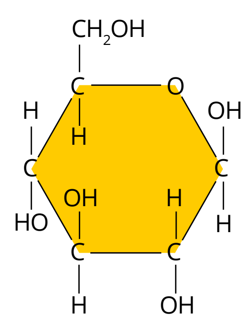

FIGURE 3.3.22 The structure of a glucose molecule ($C_6H_{12}O_6$)

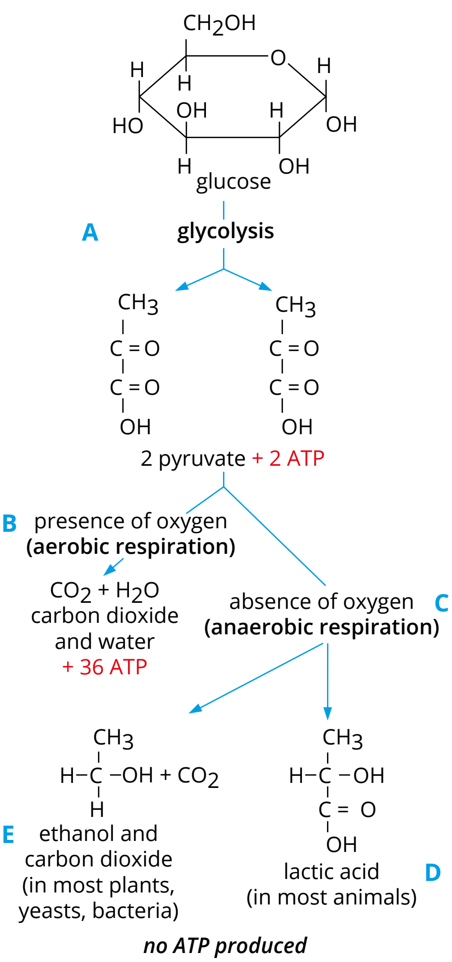

FIGURE 3.3.23 (a) During glycolysis, glucose is split into two pyruvate molecules. (b) In the presence of oxygen, aerobic respiration occurs and pyruvate is broken down into carbon dioxide and water. (c) If insufficient oxygen is present, anaerobic respiration occurs and pyruvate is converted into (d) lactic acid or (e) alcohol and carbon dioxide, depending on the type of organism.

Glycolysis

Glycolysis is the first process that takes place in cellular respiration. It involves the splitting (lysis) of glucose into two **pyruvate** molecules (Figure 3.3.23). This occurs in the cytosol of the cell and is anaerobic; that is, it does not require oxygen. Glycolysis uses two ATP molecules in breaking down one glucose molecule, but it produces four more. Therefore, there is a net gain of two ATP molecules.

The process of glycolysis is common to both aerobic and anaerobic respiration. The pathway followed after glycolysis depends on whether or not there is an adequate supply of molecular oxygen. If there is enough oxygen, aerobic respiration takes place. If there is not enough oxygen, anaerobic respiration takes place (Figures 3.3.23 and 3.3.24).

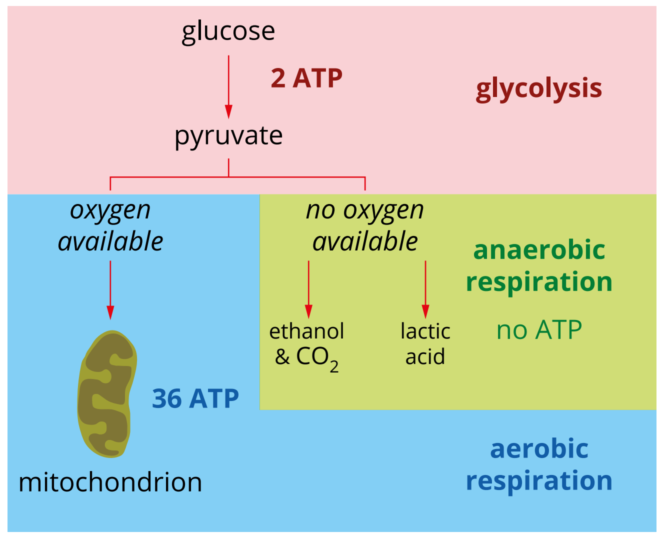

FIGURE 3.3.24 A simplified pathway of the process of cellular respiration in the presence and absence of oxygen

Aerobic respiration

When molecular oxygen is available, the next stage of cellular respiration after glycolysis is aerobic respiration. Aerobic respiration occurs in mitochondria and converts ADP to ATP. During aerobic respiration, the two pyruvate molecules produced during glycolysis (from one glucose molecule) are then broken down to produce carbon dioxide, water and 36 ATP molecules (Figure 3.3.25).

INPUTS				OUTPUTS				
glucose	+	oxygen	→	carbon dioxide	+	water	+	available energy
$C_6H_{12}O_6$	+	$6O_2$	→	$6CO_2$	+	$6H_2O$		
36 ADP	+	36 P_i	→	36 ATP				

FIGURE 3.3.25 Cellular respiration with aerobic respiration involves the transformation of glucose, oxygen, ADP and phosphate into carbon dioxide, water and ATP.

Anaerobic respiration

If there is not enough oxygen available, aerobic respiration does not occur. Instead, the pyruvate passes into an anaerobic pathway. This anaerobic pathway is known as anaerobic respiration or **fermentation**. Anaerobic respiration occurs in the cytosol, not in the mitochondria. During anaerobic respiration, there is no further formation of ATP. The purpose of anaerobic respiration is to prevent the accumulation, or build-up, of pyruvate, which in turn allows glycolysis to continue. If pyruvate accumulates, the process of glycolysis slows, and no energy is available to the cell. Accumulation of a product can slow a chemical reaction.

In anaerobic respiration, the pyruvate produced during glycolysis is converted into either **lactic acid** (in most animals) or carbon dioxide and alcohol (in most plants and in microorganisms such as yeasts and bacteria). These two pathways are shown in Figures 3.3.23 and 3.3.24.

Aerobic vs anaerobic respiration

Aerobic respiration and anaerobic respiration both enable organisms to maintain their energy stores, but they have different functions (Table 3.3.1). For each molecule of glucose, aerobic respiration produces almost 20 times the number of ATP molecules produced by glycolysis alone. So it is not surprising that most eukaryotic cells normally carry out aerobic respiration. Most eukaryotic cells only rely on anaerobic respiration to continue the generation of ATP by glycolysis for very short periods (seconds), or when there is not enough oxygen available for aerobic respiration.

TABLE 3.3.1 Comparison of aerobic and anaerobic respiration in eukaryotic cells

	Aerobic respiration	Anaerobic respiration
location	mitochondrion	cytosol
oxygen required	yes	no
waste products	carbon dioxide and water	carbon dioxide and alcohol (in plants, fungi and some bacteria) lactic acid (in animals)
ATP produced	2 in glycolysis 34 in aerobic respiration	2 in glycolysis 0 in anaerobic respiration
net ATP produced	36	2

Transporting oxygen to cells

Organisms that use aerobic respiration need to transport oxygen to their cells. In mammals, oxygen is made available to cells via the lungs. In the lungs, oxygen diffuses from the alveoli into the blood (Figure 3.3.26). The oxygen combines with a protein called haemoglobin to form oxyhaemoglobin, which is transported to cells by the body's circulatory system. Oxygen is then released from the oxyhaemoglobin and diffuses into the cells. The cells use the oxygen for aerobic respiration, which supplies them with the energy they need to function. In heterotrophic cells, a reverse process removes the waste carbon dioxide produced by aerobic cellular respiration. You will learn more about the respiratory system in Chapter 5.

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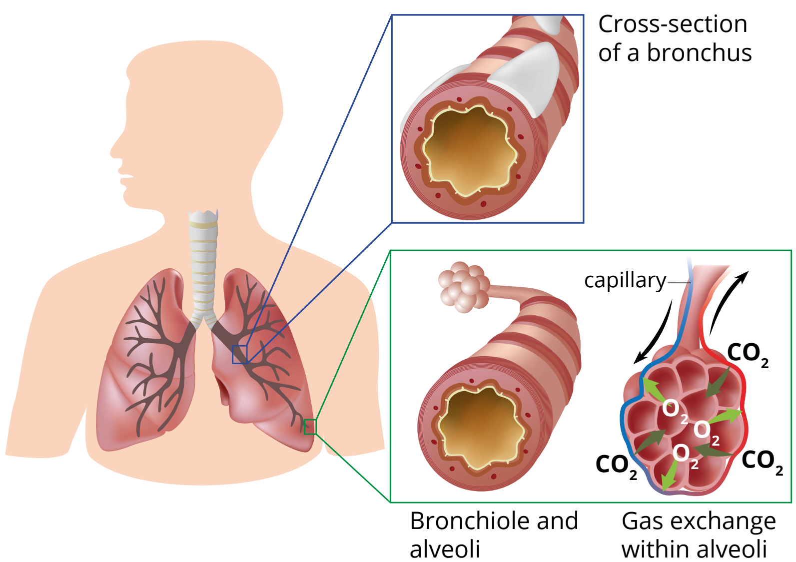

FIGURE 3.3.26 In mammals, lungs take in the oxygen needed for aerobic respiration in cells, and breathe out the carbon dioxide that is produced as waste. This process is known as gas exchange, or is simply referred to as respiration (not to be confused with cellular respiration).

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Mitochondria

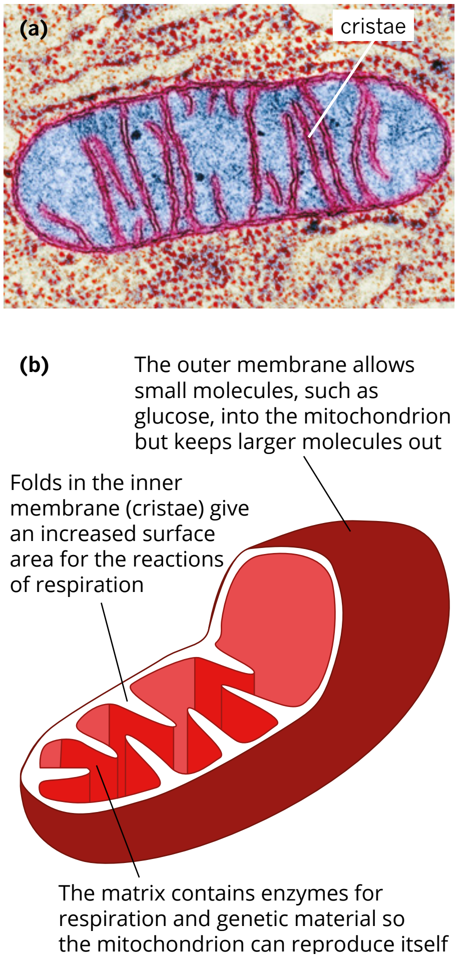

FIGURE 3.3.27 (a) A coloured TEM image of a mitochondrion, the cell organelle in which aerobic respiration occurs in eukaryotes. The outer membrane and the folds of the inner membrane (cristae) are coloured pink. (b) The structure of a mitochondrion is closely related to its function.

Mitochondria are often called the power plants of cells, because they produce most of the ATP used in a cell. Mitochondria are relatively large organelles with a double membrane. The inner membrane forms many folded layers called **cristae** (Figure 3.3.27). The cristae provide a large surface area on which the chemical reactions of aerobic respiration take place.

The number of mitochondria in a cell is related to the cell's energy requirements. Very active cells, such as muscle cells and neurons (nerve cells), may have thousands of mitochondria (Figure 3.3.28).

Some important points about glycolysis and aerobic respiration in mitochondria are summarised in Figure 3.3.29 and Table 3.3.2.

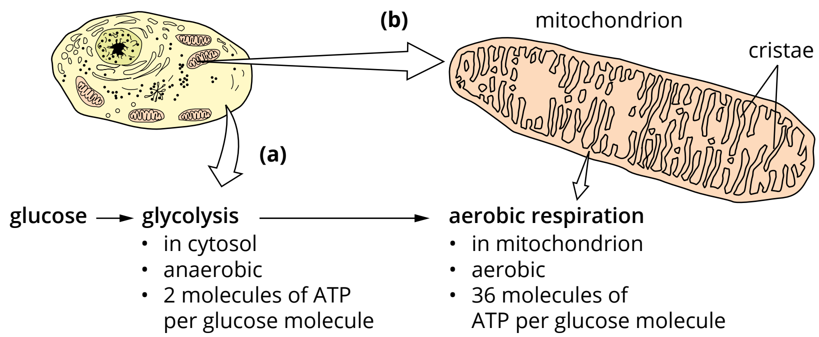

FIGURE 3.3.29 (a) Glycolysis occurs in the cytosol and produces two molecules of ATP per glucose molecule. (b) Aerobic respiration occurs in mitochondria and generates another 36 molecules of ATP.

Just as photosynthesis is often simplified into a single equation (Figure 3.3.7), cellular respiration can also be represented by a generalised chemical equation (Figure 3.3.25). Again, in reality, cellular respiration is a complex biochemical pathway involving many steps, each controlled by enzymes. At the simplified level, the two processes appear to be reciprocal (opposites). While this is not strictly true, it is a useful way to remember the overall equations and the importance of both in biological systems. The difference between the two is that photosynthesis uses solar energy and chlorophyll, whereas cellular respiration uses chemical energy only, and does not require light or chlorophyll.

The reactions that occur in glycolysis and aerobic cellular respiration can be summarised as follows:

Word equation: glucose + oxygen → carbon dioxide + water + energy (ATP)

Chemical equation: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ and $ADP + P_i \rightarrow ATP$

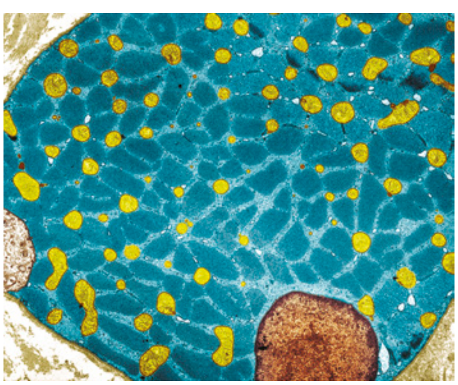

FIGURE 3.3.28 A coloured TEM image of a skeletal muscle cell. The numerous mitochondria are coloured yellow.

TABLE 3.3.2 Summary of cellular energy transformations

	Photosynthesis	Cellular respiration	
		aerobic	anaerobic
location	chloroplasts	cytosol and mitochondria	cytosol
reactants	water and carbon dioxide	glucose and oxygen	glucose
products	glucose, oxygen and water	water, carbon dioxide and ATP	• lactic acid (animals) • ethanol and carbon dioxide (plants, fungi)

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Anaerobic Earth

The surface of Earth was an anaerobic environment before photosynthesis developed (Figure 3.3.30a). This was a world without plants, animals or insects, but many organisms still managed to survive without free oxygen. At this time, glycolysis was probably the most common method of storing energy in living cells. When photosynthetic organisms evolved and multiplied, they produced so much oxygen that Earth's atmosphere changed (Figure 3.3.30b). This new aerobic environment allowed the evolution of organisms—including humans—that relied on oxygen gas to survive.

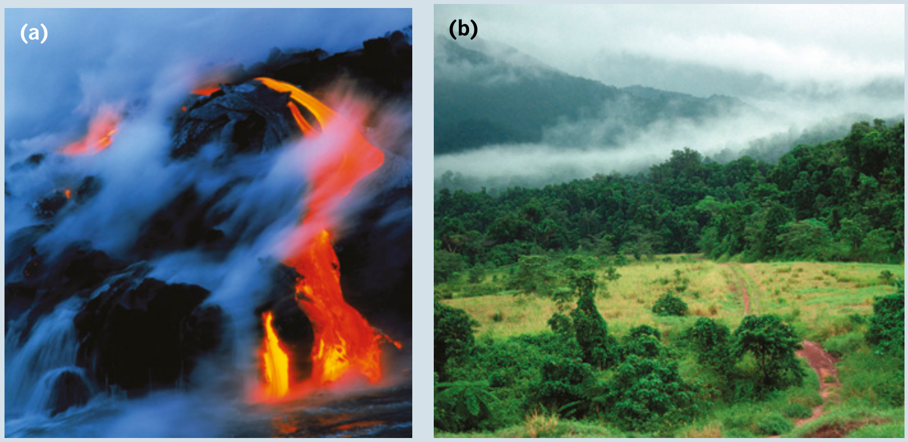

FIGURE 3.3.30 Life on Earth has changed drastically from an anaerobic environment (a) to an aerobic environment (b) that supports the variety of life we see today.

REMOVAL OF CELLULAR PRODUCTS AND WASTES IN EUKARYOTIC CELLS

During the biochemical processes of photosynthesis and cellular respiration, by-products are produced by cells. Cells need efficient ways to remove these waste products so they don't accumulate in the cell and inhibit normal cell functions. For example, a build-up of pyruvate from glycolysis would slow further glycolysis (Figure 3.3.23). Cells, tissues, organs and systems have several ways of removing waste products from an organism.

Cellular waste removal

Eukaryotic cells have organelles that are specialised for processing and removing waste products from cells. Two important structures that process and remove wastes inside cells are lysosomes and **proteasomes**.

Lysosomes

Lysosomes are small vesicles that are filled with digestive enzymes. The lysosomes float in the cytosol of the cell, fusing with vesicles that contain waste products or damaged cellular structures. The digestive enzymes inside lysosomes break down waste products into smaller molecules.

Once the waste products are small enough, they are either reused by the cell, or transported out of the cell through the cell membrane via exocytosis. The removal of waste products via exocytosis is covered in Section 3.1.

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Lysosomes are found in all animal cells and some plant cells. Lysosomes are examined in more detail in Chapter 2.

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Proteasomes

Proteasomes are protein complexes that degrade damaged proteins by breaking their peptide bonds. They are found in the cytoplasm and nucleus of all eukaryotic cells, and in archaea and some bacteria.

Proteasomes regulate the concentrations of proteins inside the cell and destroy proteins that are misfolded. The chemical reaction that proteasomes use to degrade proteins is called proteolysis, and the enzymes that catalyse these reactions are called proteases.

Waste-removing organs and systems

Waste removal not only occurs at the cellular level but also within tissues, organs and systems that are specialised for this function. Two important organs in the excretory system of mammals are the liver and kidney.

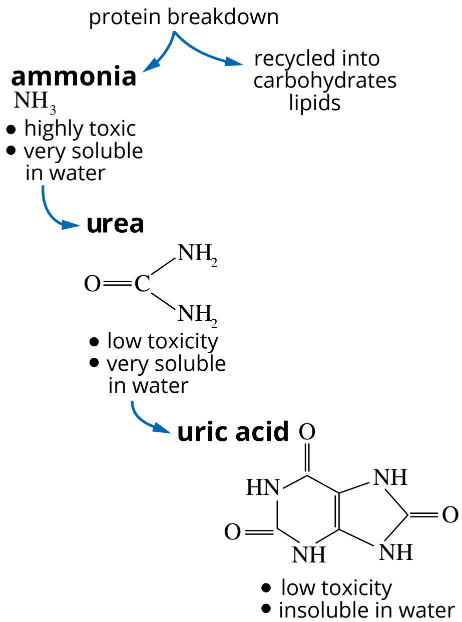


FIGURE 3.3.31 The biochemical pathway that produces three important nitrogenous wastes from the breakdown of proteins in animals

Urea is a larger molecule than ammonia, and has more nitrogen atoms. It is much less toxic than ammonia and is highly soluble in water. Although converting ammonia into urea requires energy, it is a strategy that is a successful adaptation to life on land.

The liver prepares wastes

The **liver** in mammals performs many different functions and has a central role in the maintenance of a stable internal environment. In addition, it is responsible for preparing various substances for excretion. It detoxifies a variety of harmful chemicals, such as alcohol and some drugs. It is also responsible for breaking down amino acids to release **ammonia**, which it then converts largely into **urea**. The waste products from these processes travel in the bloodstream to the kidneys for excretion in the urine.

The liver also destroys worn-out red blood cells, producing bile pigments from the breakdown of haemoglobin. **Bile** pigments (along with bile salts, which emulsify fats as part of digestion) are stored in the gall bladder before they are released into the **lumen** of the intestine. From here, the bile joins undigested food to be excreted in the faeces, a process known as **egestion** in mammals. Bile pigments are one of the few substances excreted into the gut.

The first nitrogenous waste to be formed from the breakdown of protein is ammonia. Ammonia can be converted into urea or **uric acid** (Figure 3.3.31). This process comes at an energy cost, but makes the waste less toxic.

Neither urea nor uric acid are of any further use to most animals. But a rare few animals, such as sharks, are adapted to maintain high levels of nitrogenous wastes—particularly urea—within their body to aid in water regulation (Figure 3.3.32).

The blood of most sharks is isotonic to their marine environment. This means that there is an equal concentration of solutes (dissolved substances) in both their body and the ocean. They maintain osmotic balance with the seawater and are known as **osmoconformers**. Unlike seawater, with its dissolved salts such as sodium chloride, the shark uses dissolved urea in its body fluids. The urea is retained after the production of nitrogenous wastes. The difficulty with this strategy, and the reason other vertebrates excrete their urea, is that urea destabilises many enzymes necessary for the body's chemical reactions. A shark counters this effect with another solute: tri-methyl amine oxide (TMAO). After a shark dies, the urea and TMAO in their rotting flesh convert into distinctive, foul-smelling chemicals.

FIGURE 3.3.32 The great white shark is an osmoconformer. It uses urea dissolved in its body fluids to balance soluble salts in the sea water around it.

Nitrogenous waste (or nitrogen waste) consists of chemical compounds containing nitrogen atoms (N), which must be excreted before they poison an organism's cells. These compounds are ammonia (the most toxic), urea, uric acid and creatinine. All of these substances are produced from normal protein metabolism.

Figure 3.3.33 shows the different forms of nitrogenous waste excreted by different species.

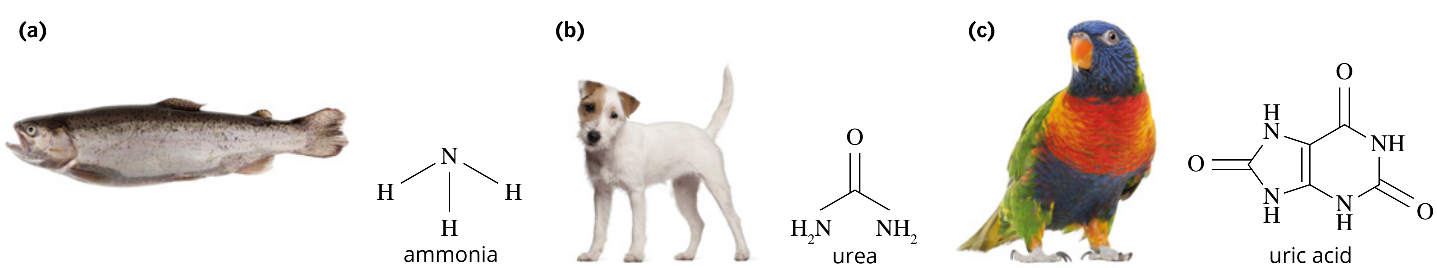


FIGURE 3.3.33 Nitrogenous waste is excreted by each species in a form suitable for their environmental needs. (a) All freshwater fish and most invertebrates excrete ammonia; (b) mammals and most marine fish excrete urea; (c) birds, reptiles and insects excrete uric acid.

The kidneys excrete wastes

The kidneys of all vertebrates perform four main steps:

- **filtration** of blood
- **reabsorption** of useful substances back into the blood
- active **secretion** of extra wastes into the filtrate (forming waste called urine)
- elimination of the unwanted urine from the organism.

Within the kidney are large numbers of microscopic functioning units called **nephrons**. Fish have the least complex nephrons, while mammals have the most complex. The two human kidneys contain approximately one million nephrons each, all within a vital organ that is roughly fist-sized in an adult.

During its routine circulation around the body, blood passing through each kidney is filtered through the blood vessel walls to form a primary filtrate in the nephron tubules. The filtrate has the same composition as blood plasma, except that large protein molecules, as well as blood cells, have been filtered out. Most of the useful substances in the primary filtrate are quickly reabsorbed as it passes along each nephron tubule. Some extra unwanted substances may be secreted into the fluid in the tubule before it passes as urine from the kidney to the bladder. The formation of urine involves passive filtration, selective reabsorption and secretion, and the passive removal of water (Figure 3.3.34).

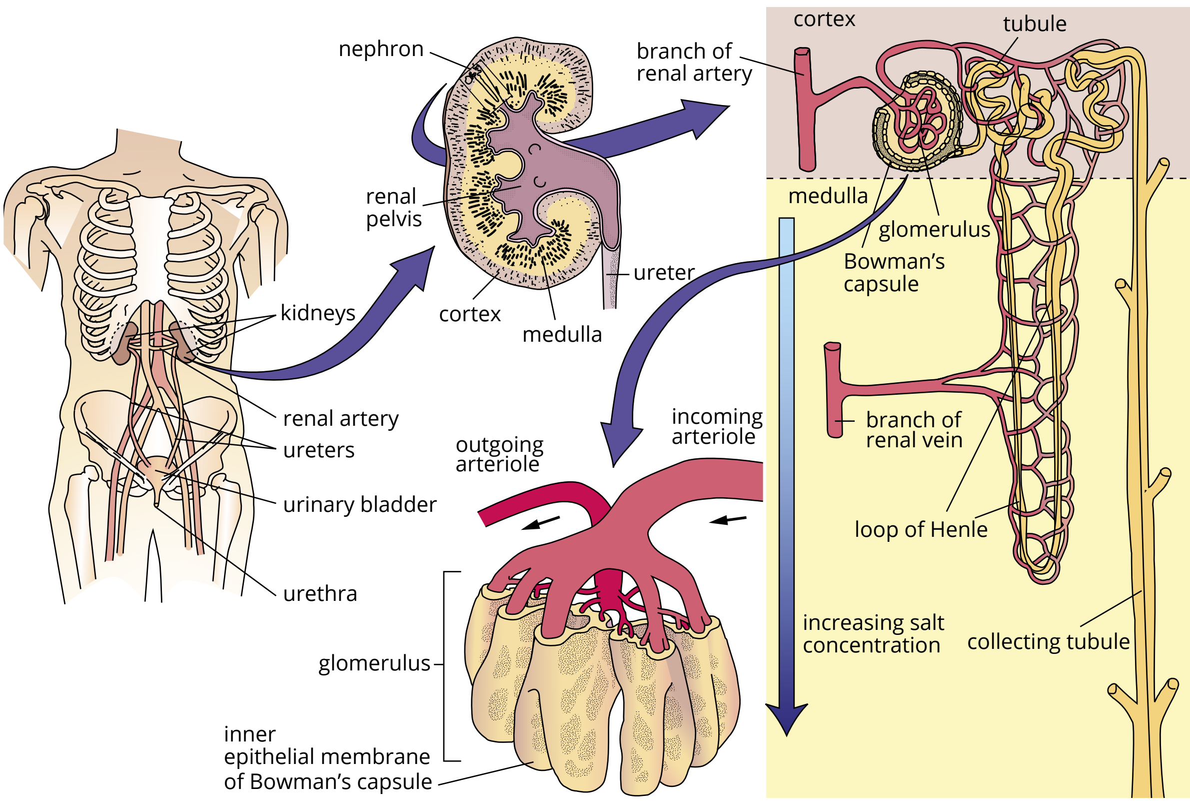


FIGURE 3.3.34 The human excretory system

These processes regulate the concentration of different salts in the blood, including those responsible for maintaining the pH of body fluids within closely controlled limits. Mammals conserve water by producing urine that is more concentrated than body fluids. In some mammals, such as the desert-dwelling bilby (Figure 3.3.35) or hopping mouse (Figure 3.3.36), the ability to produce concentrated urine is related to the degree of water stress experienced in their normal environments.

FIGURE 3.3.35 Desert-dwelling animals such as the bilby (*Macrotis lagotis*) can produce highly concentrated urine, which minimises water loss.

BIOLOGY IN ACTION N

Spinifex hopping mouse and osmolarity

The spinifex hopping mouse (*Notomys alexis*) is a small native rodent that inhabits sandy soil areas of central and western Australia (Figure 3.3.36). This species is known as Dargawarra or Tarrkawarra to local Indigenous people. *N. alexis* eats mainly dry seeds, as well as plants and insects when they are available. This species has the distinction of having the most efficient kidneys and the most concentrated urine of any mammal recorded.

One research project compared the hopping mouse with the house mouse (*Mus musculus domesticus*). The study found that *N. alexis* can reduce urine volume and increase urine concentration much more rapidly when water deprived, and still stay healthy. The ability to concentrate urine rapidly is characteristic of a well-insulated, relatively large medulla region in the kidney and a long loop of Henle (see Figure 3.3.34). The water-deprived hopping mice also produced dilute urine very rapidly following rehydration. Both adaptations help to explain the hopping mouse's success at living in extreme desert conditions.

Urine concentration is known as **osmolarity**. Osmolarity is measured in osmoles (Osm) of solute per litre (L) of solution (Osm/L). Since 1 litre (L) of pure water has a mass of 1 kilogram (kg), osmolarity figures are often given per kg of water. A large value means more concentrated urine that has more dissolved solids and less water.

In humans, osmolarity can range from approximately 50 to 1200 mOsm/kg of H_2O, depending on whether the person has recently drunk a large quantity of water (the lower number) or has gone without water for a long time (the higher number). Over 24 hours, the healthy average range for humans is between 500 and 800 mOsm/kg of H_2O.

Mammals that are capable of higher osmolarity are rats (approximately 3000 mOsm/kg H_2O), hamsters and mice (approximately 4000 mOsm/kg H_2O), and chinchillas (approximately 7600 mOsm/kg H_2O). Compare these values with *N. alexis*, which can produce a urine concentration as high as 8000 to 9000 mOsm/kg H_2O.

FIGURE 3.3.36 (a) A field worker holds the spinifex hopping mouse, *Notomys alexis*. The adult rodent is around 100 mm in body length with a tail longer than their body. *N. alexis* has adapted to its dry, hot environment by reducing water loss. (b) In central Australia, *N. alexis* emerges at dusk from its burrow, which may extend a metre below the surface. They can produce the most concentrated urine of any mammal recorded to date.

BIOLOGY IN ACTION AHC IU S

Plants keep their internal balance

As with all living things, plants sometimes produce excess substances. To maintain an internal chemical balance, plants have many ways to remove excess substances without the need for the specialised systems and organs that animals have.

- Excess gases O_2, CO_2 and H_2O (water vapour) diffuse into the air from open pores called stomata in the leaves, and sometimes from openings in bark on tree trunks called lenticels.
- Leaves, bark, flowers and fruit dropping from trees carry waste away with them.
- Resin and gum ooze in drops out of the branches of trees such as gums, pines and mango. This is often a response to damage of the woody parts. Gum forms from the breakdown of cellulose, the strengthening chemical of plant cell walls. Plant resins are valued as amber, a fossilised form used in jewellery (Figure 3.3.37a). They are also used to produce varnishes and adhesives, such as epoxy glue; and some perfumes and incense, such as frankincense. Indigenous Australians have long used the sap and resins from eucalyptus trees for a range of purposes (Figure 3.3.37b). For example, river red gums provide sap that can be prepared as an antiseptic for cuts and sores, and bloodwood (*Corymbia opaca*) sap is used for a toothache.
- Essential oils from citrus, lavender, eucalyptus, tea tree and other plants are released into the air as scented vapours.
- Alkaloids are nitrogenous waste. Examples in plants that are used by people are nicotine, caffeine and morphine.
- Tannins are chemicals produced by many plant species. Their bitter taste probably offers protection, but they must be stored safely inside plant tissue to prevent their destructive effect on proteins. The brown colour in water flowing from boggy areas is due to leaching of tannins from peat plants. Bark from oak trees has long provided tannin for treating (tanning) leather. The dry-mouth sensation from drinking some wines is due to the natural tannins released from grape skins.
- Latex is a sticky, opaque, white emulsion exuded from plants such as oleander, poinsettia, frangipani, mulberry and fig. It is a defence mechanism against insects.
  - Natural rubber is an important latex product, now usually replaced by synthetic materials (Figure 3.3.37c).
  - Opium is dried latex from opium poppy seed heads.
  - Chewing gum was traditionally made with latex from the chicle trees of Central American countries and jelutong trees of Malaysia and Thailand (Figure 3.3.37d).

FIGURE 3.3.37 (a) Amber is fossilised resin, a sticky exudate from some trees that often traps and preserves small invertebrates. (b) Sap oozes from a river red gum trunk. (c) Natural rubber is a latex product traditionally tapped from small incisions in the trunk of rubber trees. (d) Today, chewing gum is usually made from synthetic products rather than from traditional tree gums, such as chicle. A move back to natural products has seen small community-based industries producing items such as this chewing gum kit.

3.3 Review

SUMMARY

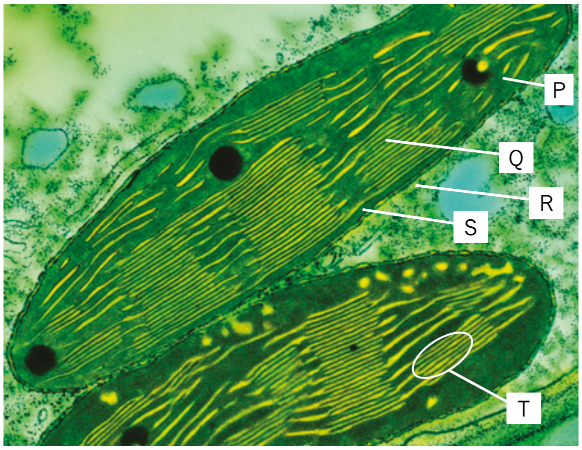
- During photosynthesis, plants trap solar energy and use it to split water molecules (H_2O) into hydrogen and oxygen (photolysis). Carbon dioxide is then combined with hydrogen to produce glucose in a carbon fixation process. Excess oxygen is released to the environment as a waste product.
- Through photosynthesis, solar energy is transformed to chemical energy, which is stored in the bonds of glucose molecules.
- Photosynthesis occurs in cell organelles of green plants called chloroplasts that contain chlorophyll.
- Light intensity, carbon dioxide availability and temperature may limit the rate of photosynthesis.
- The reactions that occur during photosynthesis can be summarised by an overall equation:
  - word equation: water + carbon dioxide → glucose + oxygen
  - chemical equation: $6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$
- Plants also carry out the biochemical process of cellular respiration, which uses oxygen and glucose.
- The reactions that occur during cellular respiration can be summarised by an overall equation:
  - word equation: glucose + oxygen → carbon dioxide + water + energy (ATP)
  - chemical equation: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ and $ADP + P_i \rightarrow ATP$
- Photosynthesis generally occurs only during daylight, but cellular respiration occurs continuously.
- The light compensation point for a plant is the level of light at which the rates of photosynthesis and cellular respiration are equal. At this point, the amount of oxygen produced by a plant and the amount used is equal, so there is no net release of oxygen as waste.
- Cells use chemical energy in the form of ATP (adenosine triphosphate) to carry out cell functions.
- Cells produce ATP by the process of cellular respiration.
- Cellular respiration takes place in two stages. The first stage is glycolysis, and the second stage is either aerobic respiration (if oxygen is available) or anaerobic respiration (if oxygen is not available).
- Glycolysis in the cell cytosol generates two ATP molecules and two molecules of pyruvate per molecule of glucose. Glycolysis does not require oxygen.
- In the aerobic respiration stage, pyruvate passes into mitochondria, where it is broken down to carbon dioxide and water along a complex biochemical pathway. For every two molecules of pyruvate, a further 36 molecules of ATP are generated.
- In anaerobic respiration, pyruvate is converted in the cytosol to lactic acid (in most animals) or alcohol and carbon dioxide in plants, bacteria and yeasts (fermentation), and no more ATP is produced.
- Enzymes control both the biochemical pathways of photosynthesis and cellular respiration.

KEY QUESTIONS

1 State whether each of the following statements is true or false.
  - **a** Chlorophyll is a pigment that causes green colouring of leaves.
  - **b** Chloroplasts are pigments that absorb light.
  - **c** Chlorophyll is located in the thylakoid membranes.
  - **d** Chlorophyll absorbs light energy, which is then transformed into chemical energy.

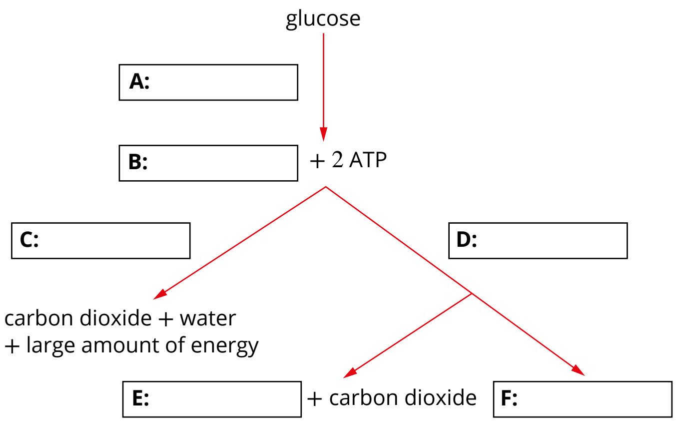
2 Write the general equation for photosynthesis and calculate how many glucose molecules would be produced from 24 water (H_2O) and 24 carbon dioxide (CO_2) molecules.

3 The figure to the right shows a transmission electron microscope image of a chloroplast. Identify structures P, Q, R, S and T.



4 Describe the light compensation point and explain what happens at this point.

5 The figure below is a summary of the major processes that occur during cellular respiration. Provide the most appropriate labels for A, B, C, D, E and F.



6 What is the difference between aerobic and anaerobic respiration?

7 What is the major benefit to cells in using aerobic respiration rather than anaerobic respiration?

8 Explain why photosynthesis is not the exact opposite of aerobic respiration, even though the equations appear to be the reverse of each other.

9 Lysosomes and proteasomes are two important cellular structures that remove waste products. What are the mechanisms that these structures use to remove waste?

10 The following diagram represents a nephron from a mammalian kidney.

a State the function of a kidney in the excretory system.

b Identify at least two differences that would be expected between the fluid at locations X and Y in a healthy person.

3.4 Enzyme activity in cells

BIOLOGY INQUIRY CCT N WE

Removing hydrogen peroxide from cells

How do cells coordinate activities within their internal environment and the external environment?

COLLECT THIS…

- 1 uncooked potato
- coarse grater
- thin kitchen cloth (must be porous for straining the potato puree)
- hydrogen peroxide (H_2O_2) 3% or 6% solution (this is a bleach, from a supermarket or chemist)
- beaker (approximately 300 mL)
- syringe or dropper

DO THIS…

1. Grate the raw potato until you have a puree. Take care with sharp edges.
2. Place the kitchen cloth over the opening of the beaker and secure it with a rubber band.
3. Strain the potato puree through the cloth until there is approximately 20 mL of potato juice in the beaker.
4. Using the syringe or dropper, add 2 mL of 3% hydrogen peroxide to the beaker.
5. Observe the biochemical reaction that takes place.

RECORD THIS…

Describe what happens when the potato comes in contact with hydrogen peroxide. This is an important biochemical reaction in cells.

Present an explanation for this biochemical reaction to your class.

REFLECT ON THIS…

How do cells coordinate activities within their internal environment and the external environment?

How would the biochemical activity change if you changed the concentration of hydrogen peroxide?

What can cells do to make toxic substances harmless using a biochemical reaction?

DS 1.1

Cells have mechanisms that regulate biochemical reactions to ensure the final product is not overproduced or underproduced. Enzymes are protein molecules that catalyse biochemical reactions and regulate biochemical pathways. The highly specific nature of enzymes ensures that particular enzymes only bind to particular substrates, catalysing specific chemical reactions. Enzyme activity is altered by the environment around the enzyme and sometimes by the availability of cofactors.

Enzymes accelerate the rates of biochemical reactions that would otherwise take place more slowly. Their action is specific: they catalyse (cause or accelerate) only one type of reaction.

FEATURES OF ENZYMES

Most enzymes are globular-type protein molecules. This means they are formed from long chains of amino acids that coil and fold into a compact structure. Most globular proteins are soluble. The 3D shape of an enzyme molecule is critical to the enzyme's activity. Because the molecules are so complex and have a large number of atoms, illustrations use computer-generated models to represent their structure.

The main features of enzymes are their **specificity** for a **substrate**, their **catalytic power** and their capacity to catalyse repeated **reactions**.

- Specificity—different enzymes act as **catalysts** for different biochemical reactions by binding to a specific type of molecule, called a substrate (Figure 3.4.1). Although some enzymes have evolved to be highly specific, binding to only one substrate and catalysing one specific reaction, other enzymes can act on multiple substrates that are similar and catalyse multiple reactions.
- Catalytic power—enzymes do not make reactions occur that would not occur on their own; they only make reactions occur more quickly (sometimes more than a million times faster).
- Enzymes are not consumed when they catalyse reactions—they do not form part of the products of the reactions they catalyse. At the end of a reaction, enzyme molecules are the same as they were at the beginning. This means that enzymes can be reused over and over again.

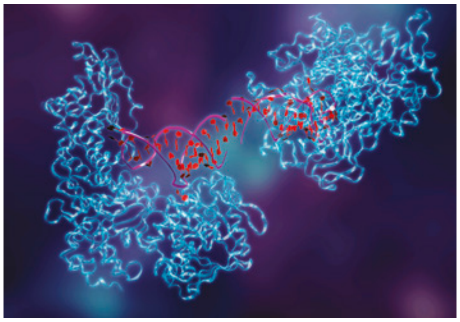


FIGURE 3.4.1 A model of an enzyme–substrate complex, where the enzyme is depicted in blue and the substrate in red. The enzyme is aconitase (blue) and the substrate is ferritin messenger ribonucleic acid (mRNA, red). Ferritin is a protein that stores iron. Aconitase helps to regulate iron levels by binding to ferritin mRNA. Once the aconitase–ferritin mRNA complex has formed, the aconitase enzyme prevents further translation and production of ferritin.

A substrate is a molecule upon which an enzyme acts. The enzyme can break down the substrate into smaller molecules, or join the substrate with other molecules to make a larger molecule. Substrates include the carbohydrates and proteins you eat, which are digested by enzyme action. Glucose is an example of a substrate used by enzymes in cellular respiration.

Catalysts are substances that accelerate the rate of any chemical reaction without themselves being changed. Enzymes are a subgroup of catalysts that catalyse reactions in living things.

Enzymes are not consumed when they catalyse reactions; they are recycled and used again many times.

BIOFILE N

Catalytic power

Catalytic power is the ability or potential of an enzyme to increase the rate of a biochemical reaction compared with the reaction occurring without the enzyme. All reactions need an input of energy to start. This is called the **activation energy**. The catalytic power of enzymes comes from their ability to reduce this activation energy, so that less energy is required for the reaction to occur (Figure 3.4.2).

One way that enzymes reduce the activation energy required for a reaction is by bringing the parts of the molecules involved in the reaction closer to each other in the active site, and positioning them where a reaction is more likely to occur.

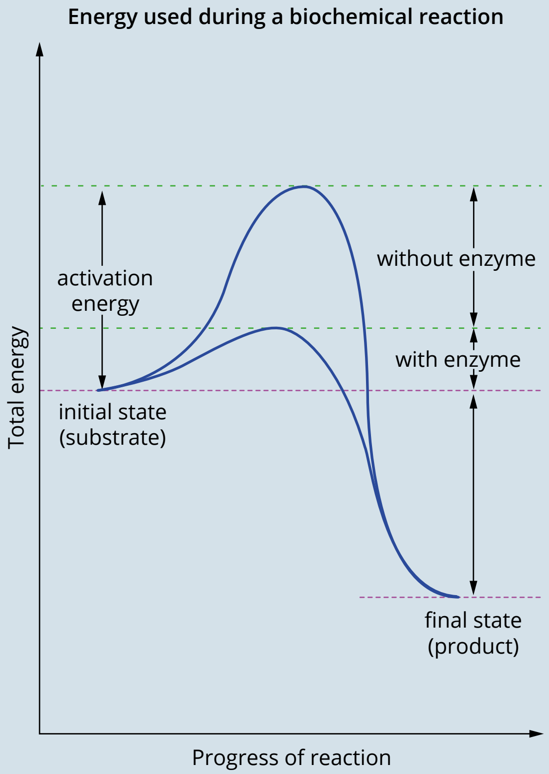


FIGURE 3.4.2 The addition of a catalyst reduces the amount of energy needed to initiate a reaction.

BIOLOGY IN ACTION ICT

Models of protein molecules

Ribbon diagrams to represent proteins were originally conceived by Jane S. Richardson in 1980. Her hand-drawn diagrams were the first schematics of 3D protein structure to be produced systematically. Soon after, computer software began to be used for this arduous task.

Today, a centralised data bank called PDB (Protein Data Bank) is full of pictorial data, and many sophisticated programs are used for drawing protein structure: UCSF, RasMol, Phobius, Chimera, TopDraw and Pro-origami are just a few examples. An easy way to gain an overview of PDB is to look online at PDBsum and access the Enzyme link, which is updated daily. On 4th March 2017, there were 39,207 PDB-enzyme entries.

The original style of ribbon diagram is still used in digital versions, and is sometimes known as a cartoon. They are simple, yet powerful, in expressing the visual basics of a molecular structure (twist, fold and unfold). This method allows for better understanding of a complex object, both by expert structural biologists and by other scientists, students and the general public. Ribbon diagrams are generated by interpolating a smooth curve through the polypeptide backbone. α-helices are shown as coiled ribbons or thick tubes, β-strands as arrows, and lines or thin tubes for non-repetitive coils or loops. The direction of the polypeptide chain is shown locally by the arrows, and may be indicated overall by a colour ramp along the length of the ribbon (Figure 3.4.3a).

Ball-and-stick type models are used in chemistry laboratories to show how atoms are joined into molecules. These models have been made more sophisticated, using software to construct atomic-resolution models of the target proteins from their amino acid sequence and an experimental three-dimensional structure of related homologous proteins (the template). This complex process is a specialty area that uses software packages unique to molecular modelling. The term structural bioinformatics is used for this type of modelling.

Other methods used are wireframe diagrams and space-filling diagrams (Figure 3.4.3b, c). In the science of proteomics, a biochemist will choose the type of image and software program depending on what aspect of the protein is required.

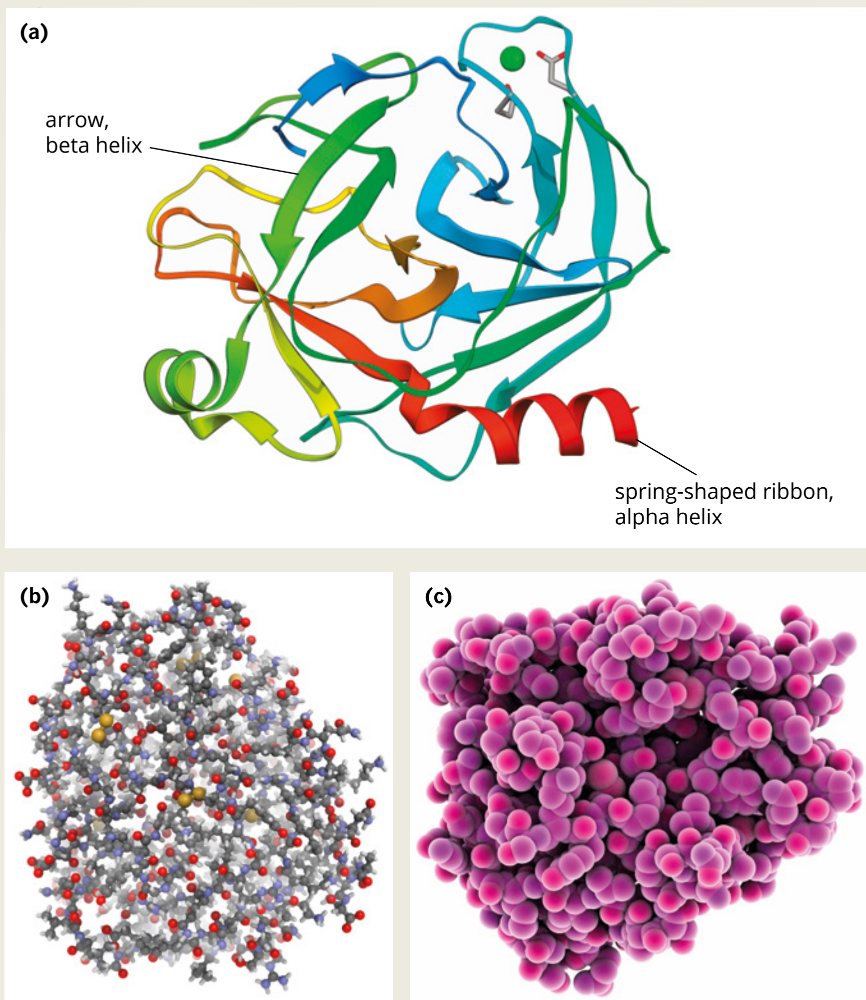


FIGURE 3.4.3 Three molecular models of the digestive enzyme trypsin, which is released by the pancreas and breaks down proteins into smaller amino acid chains. (a) Backbone and ribbon diagrams represent the folds of protein chains. The simplest backbone and ribbon diagrams have a tube that connects the positions of each amino acid. These diagrams have two special features: spring-shaped ribbons for alpha-helices and arrows that show beta-strands. (b) Wireframe diagrams have a line for each of the covalent bonds formed between the atoms. In many cases, small balls and sticks are used to make the three-dimensional shape easier to understand. (c) Space-filling diagrams have a sphere drawn around each atom to show their relative sizes.

Enzyme specificity

An important structure of enzymes is their **active site**. This is a pocket or groove-like depression in the enzyme's structure formed from the tertiary (3D) folding of the protein. Each enzyme's active site is a complex 3D shape that interacts with a specific substrate to catalyse a specific reaction. When the active site binds to the substrate, it forms an **enzyme–substrate complex** (Figure 3.4.4).

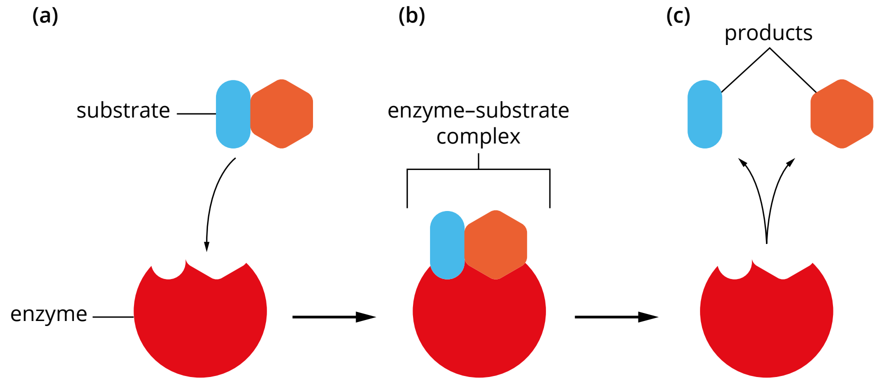


FIGURE 3.4.4 The stages of an enzyme–substrate interaction in a reaction. (a) Before an enzyme–substrate complex is formed, the substrate molecule (blue and orange) and enzyme (red) are separate. (b) The substrate molecule then attaches to the specific active site on the enzyme, forming an enzyme–substrate complex. This complex goes through a transition state where the substrate molecule is strained and broken in two. (c) The final stage is the release of the product molecules. A reaction where the substrate is broken into smaller molecules is called a catabolic reaction and usually releases energy.

Enzyme–substrate interaction models

Two models describe how enzymes and their substrates interact (Figure 3.4.5).

- The lock-and-key model describes the active site and the specific substrate as fitting together like a lock and key. If the 'key' (the substrate), does not fit into the 'lock' (the enzyme's active site), then no reaction occurs. This is the older version of the interaction model, and is now thought to be less accurate.
- The induced-fit model states that when a substrate binds to the active site of an enzyme, the active site changes shape. This model is a more accurate representation of enzyme–substrate interactions. We now know that the active site is flexible, capable of changing its shape to conform to the shape of the substrate and achieve a tighter fit.

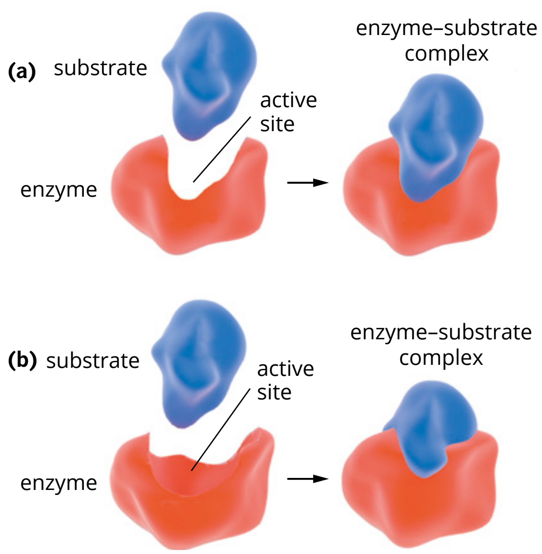


FIGURE 3.4.5 There are two major models of enzyme–substrate interaction. (a) The lock-and-key model describes the active site and substrate as fitting together like a lock and key. In this model, the substrate is the same shape as the enzyme's active site. (b) The induced-fit model describes the active site as being more flexible and changing shape to fit the substrate more tightly.

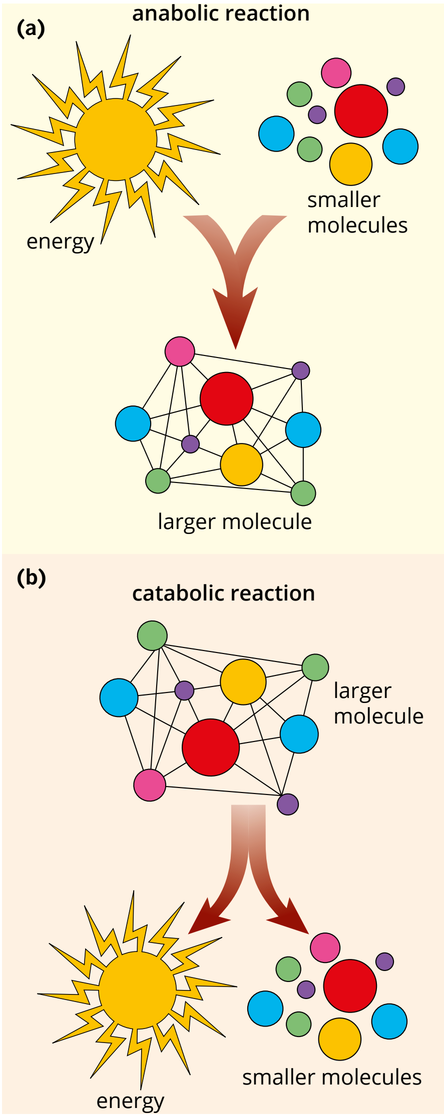


FIGURE 3.4.6 An overview of the reactions in metabolism. (a) In anabolic reactions, energy is required to combine small molecules into a larger molecule. (b) In catabolic reactions, a molecule is broken down into smaller molecules and energy is released.

FIGURE 3.4.7 A ribbon diagram of the enzyme RuBisCo from spinach. This enzyme is an important part of the biochemical pathway for photosynthesis.

Enzymes and energy in reactions

Metabolism is the collection of all the biochemical (metabolic) reactions that occur in living cells. Metabolic reactions can be catabolic or anabolic for energy, and each is enzyme-controlled (Figure 3.4.6).

- **Catabolic reactions** break down substrates. Catabolic reactions are **exergonic**, because they release energy.
- **Anabolic reactions** produce larger molecules from smaller substrates. Anabolic reactions are endergonic because they require energy to form bonds between molecules.

Some reactions are not energetically favourable and require an input of energy. To address this need for energy input, biochemical pathways sometimes couple a reaction that releases energy with a reaction that requires energy.

PLANT ENZYMES

Plants also carry out many biochemical reactions. These include photosynthesis and cellular respiration. Biochemical reactions need to be regulated in plant cells, just as they are in animal cells. Different enzymes catalyse the biochemical pathways in plants, but many of these enzymes have similar features to those in animal cells.

Photosynthesis

Enzymes play a role in photosynthesis, particularly during the light-independent stage of photosynthesis. The first step in the cycle is when carbon dioxide combines with ribulose biphosphate. An enzyme called RuBisCo catalyses this fixation of carbon dioxide (Figure 3.4.7). The cycle can then proceed to produce glyceraldehyde-3-phosphate, which the plant uses to make carbohydrates.

Because the light-independent reactions of photosynthesis are catalysed by enzymes, the rate of reaction changes as enzyme activity changes. At very low and very high temperatures, enzyme activity is disrupted, and the light-independent stage of photosynthesis slows down or stops.

Other plant enzymes

Some herbicides (chemicals that kill plants) work by blocking plant enzyme activity. A tiny herbicide molecule can attach to the active site of an enzyme and stop it from working. Such molecules are called irreversible inhibitors. Some plants have adapted to herbicides by changing one or two amino acids in their enzymes. These amino acid changes allow the enzymes to adjust their structure and continue working. As a result, these plants have become herbicide resistant.

Insectivorous plants, such as Venus fly traps, pitcher plants and sundews, produce a sticky liquid that attracts and traps insects (Figure 3.4.8). The liquid contains digestive enzymes that break down the insect body supplying extra nutrients to the plant.

Fruit enzymes

Many fruits, such as pineapple, papaya, fig and kiwifruit, contain enzymes called proteases. Proteases speed up the breakdown of proteins. Enzymes extracted from these fruits have uses as medicines, food-processing agents and dietary supplements. For example, the protease enzyme from papaya, called papain, is used for tenderising meat, treating wounds, dietary supplements and removing sediment from cold beers (Figure 3.4.9). If you have ever tried to make jelly that includes one of these fresh fruits, you will find that it doesn't set. This is because the gelatin protein has been digested by the fruit enzyme, preventing its setting action.

FIGURE 3.4.8 (a) This sundew plant has hairs that produce a sticky scented liquid, which attracts insects. The leaves enclose the trapped insects and secrete digestive enzymes that provide nitrogen nutrients for the plant. (b) An SEM image showing the digestive glands on the surface of a Venus fly trap plant. They also secrete enzymes to digest trapped insects.

FIGURE 3.4.9 Ripe papaya fruit contains a protease enzyme called papain. In dried form, papain is used as a meat tenderiser in household kitchens.

BIOLOGY IN ACTION AHC

Safe use of nardoo for food

Nardoo, *Marsilea drummondii*, is a fern that is native to wetland areas across Australia. It has spores contained in a small, hard sporocarp, which can be soaked, dried and ground to a powder (Figure 3.4.10). Some groups of Indigenous Australians, such as Yandruwandha people, roast and grind sporocarps, and then mix the powder with water to make dough, which is then cooked.

Nardoo is widely thought to be the last food resource used by the explorers Burke and Wills before their deaths in July 1861, during their expedition from Melbourne to the Gulf of Carpentaria in northern Australia. The sporocarp of the plant contains an enzyme called thiaminase, which destroys thiamine (Vitamin B1): a vitamin that is essential for many cellular processes. Without Vitamin B1, a disease called beriberi develops that affects nerve and heart function. The way Indigenous Australians prepare nardoo denatures the enzyme and makes it safe for consumption. Although Burke and Wills had observed Indigenous people using nardoo, it is thought that the explorers may not have roasted the sporocarps first, resulting in their consumption of active thiaminase. The resultant lack of thiamine in Burke and Wills' bodies, along with general malnutrition and hypothermia, are the most likely causes of the explorers' deaths. Today, cattle and sheep on grazing properties in inland Australia may die from nardoo if they eat enough of it when the sporocarps are present. Although it is fatal to mammals, nardoo is an important flood-time food for waterfowl.

FIGURE 3.4.10 Nardoo plants with sporocarps on a grinding stone

BIOFILE AHC

Indigenous use of plant enzymes

Latex

Latex is a white, sticky emulsion found in some plants. It can be harmless, such as in fig trees, but it is often irritating, corrosive or even toxic, such as in oleander. Latex often contains enzymes that digest proteins, making it a useful bush medicine for Indigenous Australians. It is used for the removal of small skin eruptions, such as warts or corns, and for cleaning the surface of infected ulcers and wounds.

River red gum sap

Indigenous Australians use the red sticky sap oozing from river red gum trees as an antiseptic for cuts and skin sores.

Medicinal plants

A study assessed the potential of seven traditional Australian medicinal plants for use in the management of hyperglycemia and type 2 diabetes. Each of the plants had anti-diabetic potential due to their enzyme activity, particularly two *Acacia* species that have traditionally been used for the treatment of general illness (Figure 3.4.11). The study found that most of the plants also had good antioxidant activity, showing promise for the management of conditions such as hyperglycaemia. Other biochemical studies have shown that plants traditionally used to treat the common cold contain chemical inhibitors of enzymes that are needed for some viruses to replicate themselves.

FIGURE 3.4.11 *Acacia ligulata* grows on sand dunes in parts of inland Australia and is used as a traditional medicine by some Indigenous Australian communities. It contains an enzyme that is being studied for its potential to treat type 2 diabetes.

FUNGI ENZYMES

Many fungi are **saphrotrophs**. They cause decay by releasing enzymes onto the dead animal or plant (Figure 3.4.12). These break down complex compounds into simple, soluble compounds that can be absorbed by the decomposer. For example, if a fungus grows on a piece of bread, it releases amylase enzymes to digest the bread starch into maltose and then absorbs the maltose (Figure 3.4.12a).

Several different fungi species cause tinea in humans using a similar action. This infection is also known as athlete's foot, because it is common around the toes and often spread through dampness in communal change rooms and shower floors at sporting facilities. Enzymes secreted by the infectious fungi soften and irritate the skin between the toes. Fungicide creams can be used for treatment, but prevention is best—by keeping the toes dry, avoiding walking barefoot on damp, communal floors and not sharing towels or socks.

Many other disease-causing fungi infect plants and animals, with their action usually coming from the enzymes secreted by the fungi to obtain the nutrients they need. The fungus group includes organisms known as mould, rot and yeast (Figure 3.4.12b).

However, fungi and their enzymes are an essential part of decomposition cycles in the environment. The combined actions of a community of diverse microbes (including fungi with their secreted exo-enzymes) convert complex organic compounds into easily assimilated **nutrients** for other species. These microbial communities are ubiquitous in nature, inhabiting both terrestrial and aquatic ecosystems. This cycling of elements from dead organic matter by heterotrophic soil microbes is essential for nutrient turnover and energy transfer in terrestrial ecosystems. Wood-rotting fungi are among the only organisms that produce enzymes capable of breaking down the tough lignin and cellulose of dead plant cell walls and wood fibre (Figure 3.4.12c).

FIGURE 3.4.12 (a) Bread mould (a type of fungus) secretes digestive enzymes that change starch into maltose. Maltose can be absorbed by the fungal cells for their nutrition. (b) An infectious fungus growing on grapes produces enzymes that damage the fruit. (c) Fungal enzymes slowly decompose dead wood. The fungus gains nutrients and the process forms an important part of the ecosystem's natural decomposition cycle.

Many useful applications have been found for fungal enzymes, some of which are listed in Table 3.4.1.

TABLE 3.4.1 Uses of fungal enzymes

Fungal enzyme	Application
cellulases	softening wood in paper production production of biofuels
peroxidases	removing pollutants in waste water treatment
lipases	degrading organic matter in sewage sludge treatment
pectinases	manufacturing yoghurt and jams
various	composting

FACTORS THAT AFFECT ENZYME ACTIVITY

When cells produce too much or too little of particular substances, or are unable to properly break down substances, the whole organism can suffer. Cells that produce excess substances are also wasting energy and resources. To account for this, cells have mechanisms that regulate biochemical reactions (metabolism) to ensure the final product is not overproduced or underproduced.

If the regulatory mechanisms fail, a variety of problems emerge for a human body—from mild to fatal. One example is known as maple syrup urine disease (Figure 3.4.13). The disease is caused by a defective group of enzymes that normally work together: an enzyme complex called the branched-chain ketoacid dehydrogenase complex. It results in a build-up of branched-chain amino acids that causes the urine to smell like maple syrup, and the blood to become acidic (low **pH**), which can result in death.

FIGURE 3.4.13 A urine sample showing the distinctive colour of maple syrup urine disease

As you've already learnt, enzymes control metabolism through the catalysis of reactions at every step of a biochemical (or metabolic) pathway. A whole pathway can be regulated through control of one enzyme. For this reason, it is important to understand the ways in which enzyme activity is affected by their environment.

All enzymes have specific conditions under which they perform at their best. Factors such as temperature, pH and the concentration of the substrate and enzyme all affect the rate of enzymatic reactions. When these conditions are optimal, enzyme activity is at its highest, the rate of reaction is at its fastest, and the biochemical pathway is operating at maximum efficiency. There are times when conditions are not optimal, leading to decreased enzyme activity and slower reaction rates. One example is the protein-digesting enzyme, pepsin, which only becomes active when it enters the low-pH environment of the acidic stomach juices (pH 2). Other examples in relation to limiting factors for photosynthesis are described in Section 3.3.

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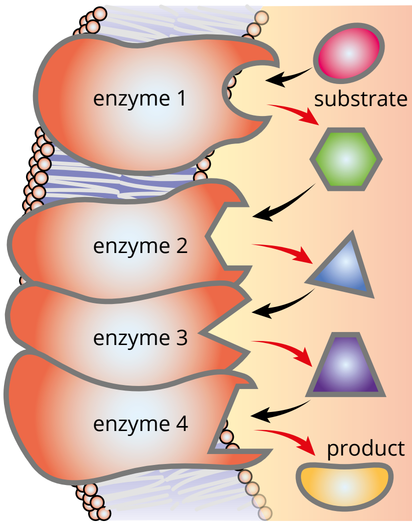


FIGURE 3.4.15 A biochemical pathway is a sequence of biochemical reactions catalysed by different enzymes. The product (indicated with the red arrow) of each reaction becomes the substrate (indicated by the black arrow) in the next reaction.

The amounts of final products and the speed at which they are produced in a biochemical pathway can therefore be controlled through the regulation of the pathway's enzymes and individual reactions. Different enzymes may be used in each step of a biochemical pathway (Figure 3.4.14). It is common to have a sequence of chemical reactions in which the product from the previous reaction is used as a substrate for the next reaction. (Figure 3.4.15). Slowing down one reaction will have an effect on all subsequent reactions.

Some biochemical pathways are linear, while some are branched, leading to many final products. Others are cycles.

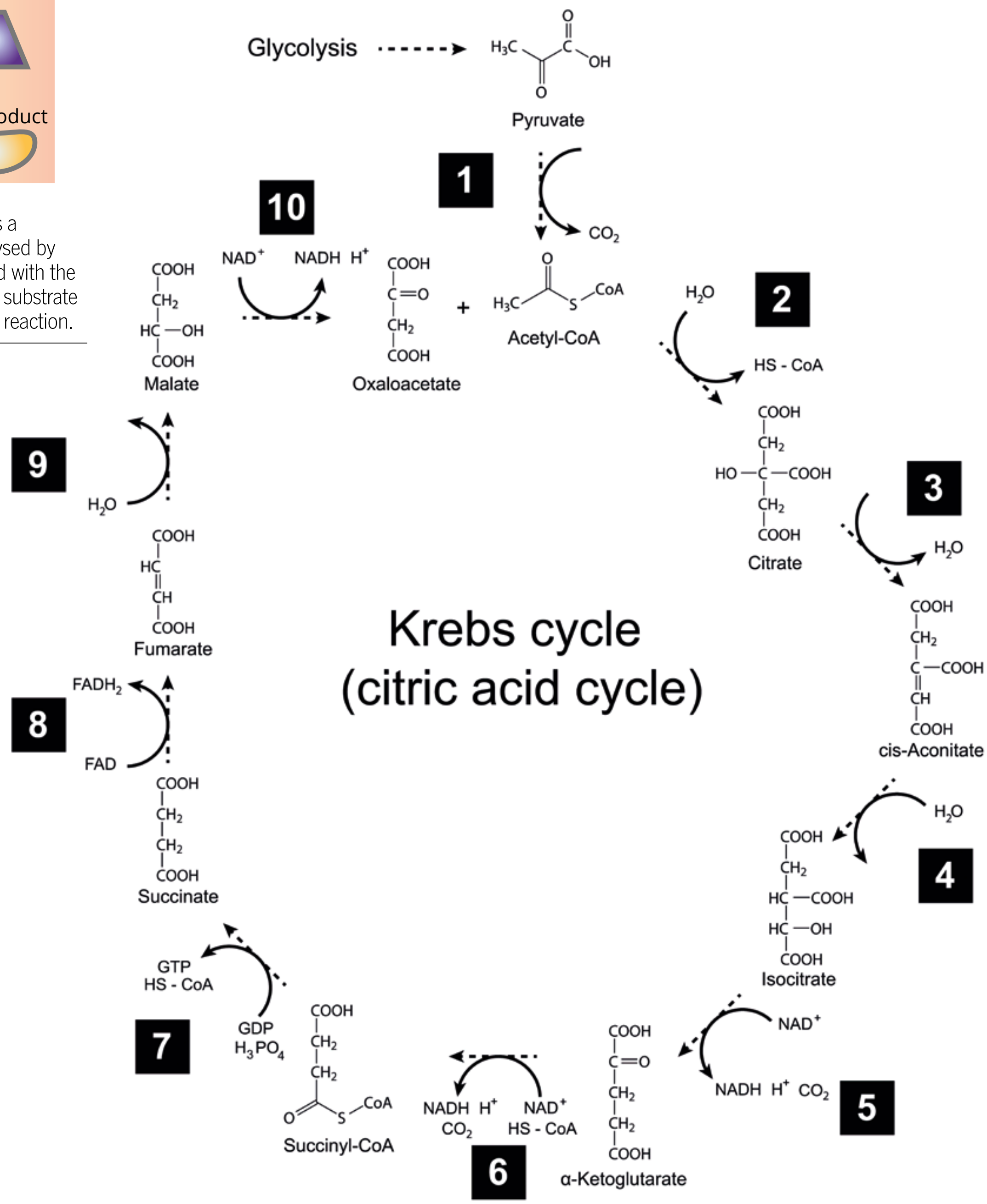


FIGURE 3.4.14 Each of the 10 consecutive steps in this biochemical pathway has its own unique enzyme. A change in activity of one enzyme affects the whole pathway, offering the opportunity for regulation of the process.

BIOLOGY IN ACTION CCT WE

Enzyme experiments

Some enzymes and substrates can be readily obtained from common food or laboratory sources and used safely for student experiments. The environment of the enzyme can be manipulated to observe changes in activity. Environmental factors include temperature, pH and concentration of enzyme or substrate. These experiments need to be carefully planned to understand the variables involved and how to collect data for the results.

Examples of easily obtainable enzymes include:

- Pepsin, which can be purchased in a dry form for laboratory use; it acts on protein, such as pieces of meat or hard-boiled egg white (Figure 3.4.16a).
- Potatoes and chopped fresh liver contain catalase, which acts on hydrogen peroxide (Figure 3.4.16b).
- Saliva contains amylase, which digests starchy food, such as bread (Figure 3.4.16c). Saliva must be used with caution, because it can carry some human diseases.
- Rennin is found in junket tablets from the supermarket; it acts to coagulate milk.

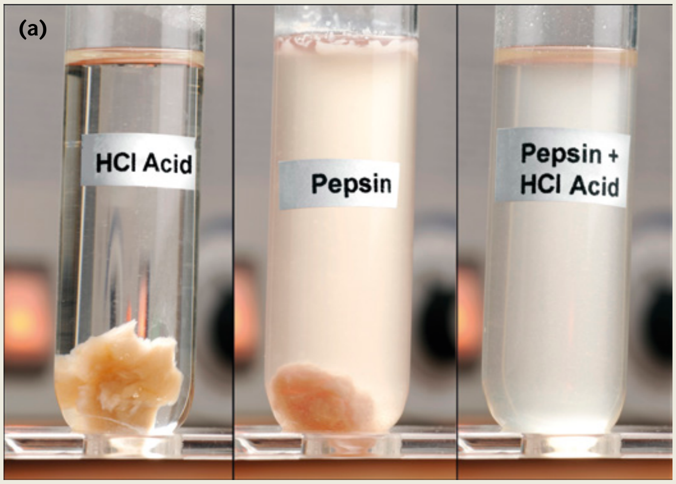


FIGURE 3.4.16 (a) Results from a digestion experiment where a piece of meat in each test tube at 35°C has been tested for protein breakdown. The enzyme pepsin is used in two tubes: one with hydrochloric acid (HCl) and one without. The tube on the left is the control with acid but no pepsin. In the tube on the right, the meat has disappeared. (b) Pieces of potato provide the enzyme catalase for a reaction with the substrate hydrogen peroxide. This sequence shows the increasing froth of oxygen bubbles released by enzyme activity. (c) This equipment is used for testing the effect of changing pH on the action of amylase enzymes.

+ ADDITIONAL CCT DD N

Metabolism of phenylalanine and PKU

Well-regulated biochemical pathways make for a healthy organism. But if anything goes wrong in a pathway, it can cause big problems with normal body functions and structure. Such problems are known as metabolic disorders and can result from faults with the enzymes that control the pathway.

One example is a disorder commonly known as PKU (phenylketonuria). Since the 1960s, PKU has been well known and every newborn baby has been tested using the Guthrie test in Australia and many other countries. Babies are screened for PKU at around four days of age using a blood sample. The blood is taken from a heel prick and collected on a Guthrie card (Figure 3.4.17).

PKU is a result of the liver being unable to produce an enzyme called phenylalanine hydroxylase. This enzyme breaks down an amino acid called phenylalanine. Phenylalanine is one of the amino acids that are present in all proteins in our food, and any excess of it is normally converted by the enzyme to another amino acid called tyrosine.

One in 10 000 babies are born in New South Wales each year with the faulty enzyme that causes PKU. Although PKU is a rare disorder, one in 50 individuals in the normal population are carriers of the recessive gene that causes it. When both parents carry this gene, there is a 25% chance that their offspring will have PKU. If phenylalanine accumulates in the blood, it is toxic to the central nervous system and can retard physical and intellectual development of the brain. Early diagnosis is essential, because of the rapid brain development that occurs in the first two years of life.

PKU is treated effectively with a low-protein diet, plus a supplement to provide tyrosine and extra vitamins and minerals that would be insufficient from the diet alone. This diet is recommended for life and is very restrictive on the foods and quantities permitted. People with PKU are unable to eat meat, nuts, bread, pasta, eggs and dairy products. Foods and drinks that contain the artificial sweetener aspartame also have to be avoided, because the sweetener is made from phenylalanine and aspartic acid.

Other enzyme faults in the same biochemical pathway can cause a range of conditions, including albinism (no skin pigment), cretinism (dwarf size, mental retardation, yellow skin), tyrosinosis (fatal liver failure) and alkaptonuria (problems with cartilage leading to arthritis and black-coloured urine).

FIGURE 3.4.17 The Guthrie test for PKU simply involves taking a drop of blood from a heel prick on a newborn baby.

Temperature

As with most chemical reactions, the rate of enzyme-catalysed reactions will generally increase as the temperature increases. This is because the warmer that particles are during a reaction, the more rapidly they move, which makes successful collisions and reactions between them more likely to occur.

However, proteins—including enzymes—can be denatured at high temperatures. When this occurs, the hydrogen bonds and **hydrophobic** interactions that create the coiled, globular, tertiary (3D) shape of the enzyme are broken. The shape of the enzyme molecule is changed so that the substrate cannot bind to it, and the reaction cannot occur. Even the induced-fit process does not provide an active site on the enzyme for the substrate molecule. Denaturation of a protein is usually irreversible. However, an Australian biochemist recently discovered how to return cooked egg white protein back to its clear, runny form. This has opened up new fields of research.

Human enzymes have their optimum activity at a temperature of 36–38°C, because that matches our normal body temperature (approximately 37°C). Many animal enzymes will begin to denature at temperatures above 40°C (Figure 3.4.18). However, some enzymes have optimum temperatures much higher than this. For example, *Taq* polymerase is an enzyme that was originally found in bacteria living in volcanic hot springs, and it has an optimum temperature of 70°C. The enzymes of each species, like their other adaptations, have evolved over time to enable the species to live successfully in their natural environment.

Denaturation is the loss of the characteristic three-dimensional shape of a protein, such as an enzyme. Denaturation prevents the functioning of the enzyme and is usually irreversible. This can happen if the enzyme is heated above its optimum temperature.

If enzymes are cooled below their optimum temperature, the rate of reaction will slow down. This is because particles will move more slowly at cooler temperatures, making successful collisions less likely. Chemical bonds are also not as flexible at cooler temperatures and conformational changes do not occur. However, enzymes are not denatured at low temperatures like they are at high temperatures. If an enzyme's environment increases in temperature, its activity and reaction rate will also increase. This is why the decomposition of food and ripening of fruit is slower in a refrigerator.

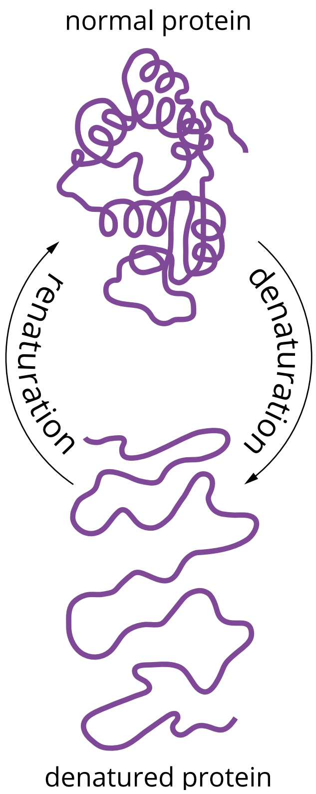


FIGURE 3.4.18 A denatured protein will lose its shape and hence its ability to function. Sometimes, a protein can renature when the chemical and physical aspects of its environment are restored to normal; but this is rare.

Enzymes at extreme temperatures

FIGURE 3.4.19 The sooty grunter fish has enzymes that enable it to survive in hot springs and acidic pH.

FIGURE 3.4.20 A glaciologist in Antarctica saws across an ice core containing frozen psychrophiles.

FIGURE 3.4.21 A TEM image of a heat-resistant enzyme complex from archaea that live in deep ocean hydrothermal vents

The sooty grunter (*Hephaestus fuliginosus*), also known as sooties or black bream, is a species of fish that inhabits coastal and inland freshwater creeks and rivers of northern Australia, from the upper Burdekin River in Queensland to the Daly River in the Northern Territory (Figure 3.4.19). Sooty grunters inhabit large freshwater streams, preferring rapidly flowing waters with a rocky bottom and sparse, aquatic plant cover. This species is also sometimes found in hot springs. Sooty grunters can tolerate acidic conditions to a pH of 4.0 and water temperatures in the range of 12–34°C. The wide tolerance range of sooty grunters is due to their metabolic enzymes being able to function in these extreme environments.

Psychrophiles are bacteria and fungi that are adapted to the extreme cold of Antarctica and the Arctic (Figure 3.4.20). These organisms have enzymes that can function in a wide range of temperatures, or two optimum temperature zones, including an optimum range as low as 0–15°C. This allows their cells to grow and carry out metabolic processes at the constant low temperatures of their cold environments.

Thermophiles are prokaryotes belonging to the Archaea domain. They tolerate very hot environments and contain enzymes with much higher optimal temperatures than those of mammals (37°C). The enzyme shown in Figure 3.4.21 can still function in temperatures up to 135°C without being denatured, making it of interest to scientists for potential industrial use.

pH

The pH scale is used to measure acidity or alkalinity (Figure 3.4.22). Enzymes have a specific pH range at which they function best. If enzymes are taken too far above or below their optimum pH, then their tertiary (3D) structure is affected, the enzyme may become denatured and the substrate may not be able to bind.

If the pH of the environment is not ideal, the micro-environment of the active site may be altered to provide a different pH and allow the reaction to take place.

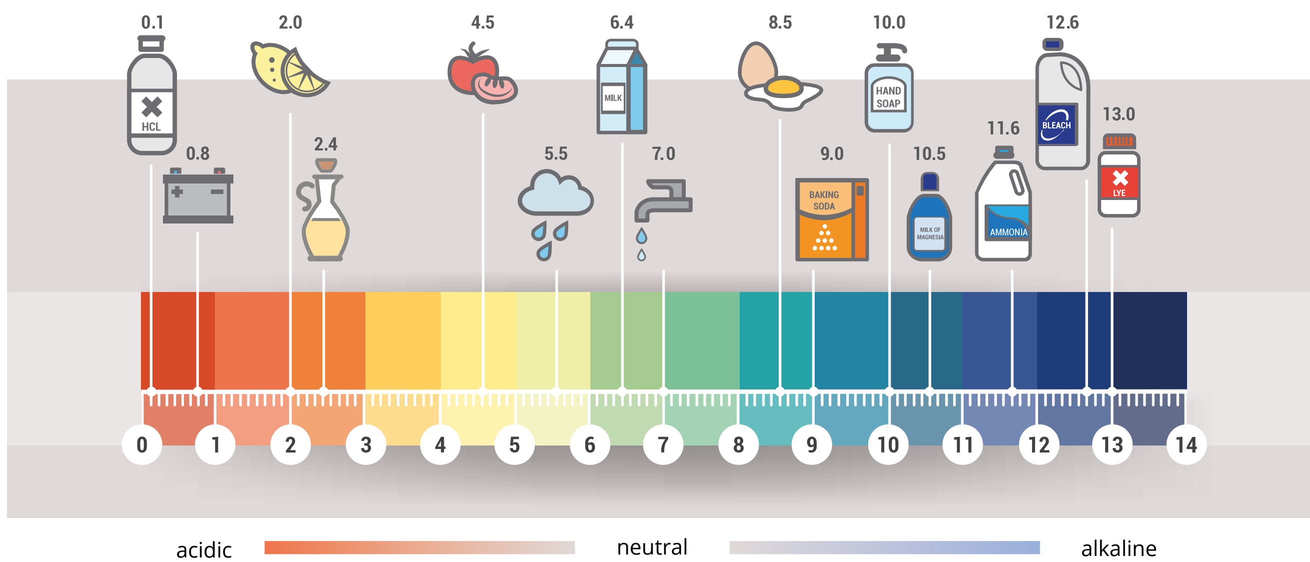


FIGURE 3.4.22 The pH scale. The normal blood pH for humans and the cytoplasm inside cells is tightly regulated at pH 7.35 to 7.45. Inside the stomach, the gastric juices are very acidic at pH 1.0–2.0, similar to lemon juice.

The optimum pH range for enzymes can be quite different, and varies depending on the function of the enzyme and where it is located. Examples include the following digestive enzymes (Figure 3.4.23).

- Amylase starts the digestion of starch in the mouth and has an optimum pH of about 7.
- Pepsin is found in the stomach and has an optimum pH of about 2 from the presence of hydrochloric acid.
- Trypsin is found in the small intestine and has an optimum pH of about 8.

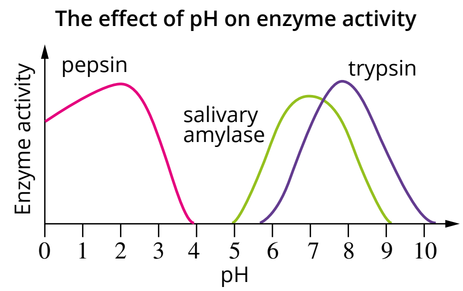


FIGURE 3.4.23 The rate of enzyme activity for three digestive enzymes in relation to pH values. At the optimum pH for an enzyme, its rate of reaction is at a maximum.

Enzyme and substrate concentration

The concentration of enzyme compared to substrate affects the rate of reaction. If the enzyme concentration is high compared to that of the substrate, the reaction will occur over a short period of time. This is because the more enzyme molecules that are available, the more active sites there will be for the substrate to bind to, and so the rate of reaction will be faster until saturation point is reached (Figure 3.4.24).

If the enzyme concentration is lower than the substrate concentration, then the reaction rate will be slow and will continue for longer. This is because there are few active sites compared to the number of substrate molecules, so the substrate molecules will have to 'wait' until there is a free active site on an enzyme molecule. When all sites are taken, the saturation point is reached.

Controlling the enzyme or substrate concentration in an organism's body is a way to regulate the speed of a biochemical pathway.

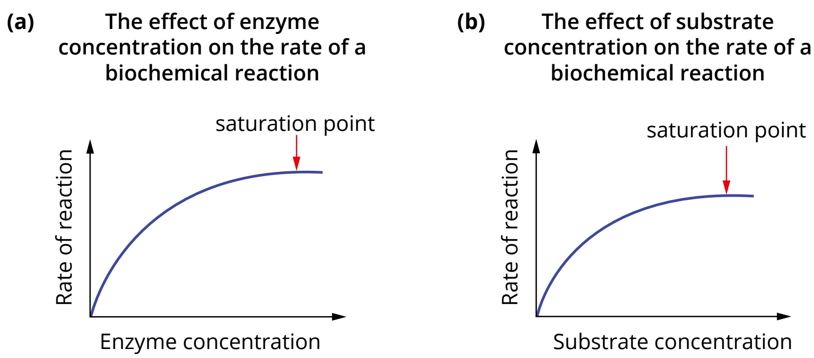


FIGURE 3.4.24 The rate of a reaction increases with (a) increasing enzyme concentration and (b) increasing substrate concentration. In each scenario, there is a point at which increasing the enzyme or substrate concentration further does not affect the reaction rate. The enzyme has reached the maximum rate of reaction. This is known as the saturation point. On the graphs, this is where the gradient stops increasing and the line becomes a plateau (horizontal).

Cellular compartmentalisation

Cellular compartmentalisation in eukaryotes helps to create an environment in which conditions are optimal for enzymes to catalyse reactions (Figure 3.4.25). Each organelle has a specific function. Within an organelle, the molecules involved in biochemical pathways that are related to the organelle's function are brought close together for reactions to take place. It also makes a different environment possible within each organelle, such as different pH and cofactor chemicals that support activity of particular enzymes. There will be high concentrations of the enzymes and substrates for that organelle's function, such as in the chloroplasts for photosynthesis and mitochondria for cellular respiration.

Another example in animal cells is the lysosome, which is a specialised sac containing digestive enzymes called acid hydrolases (Figure 3.4.25c). These enzymes are delivered to lysosomes via vesicles that bud off the Golgi apparatus. Lysosomes contain about 40 types of enzyme that break down and recycle proteins, lipids, nucleic acids and more. These enzymes function optimally in the acidic lysosomal environment, around pH 5. Lysosomes digest cell components that are past their use-by date. Specialist phagocytic cells, such as macrophages, use lysosomal enzymes to destroy ingested foreign matter.

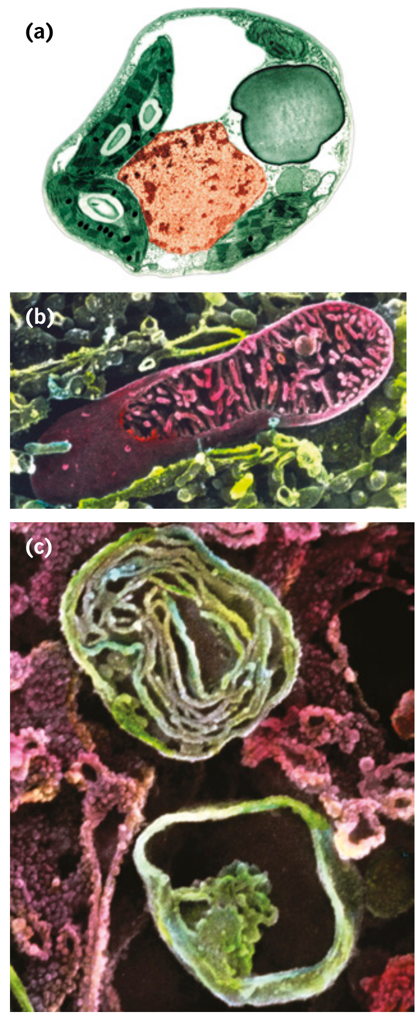


FIGURE 3.4.25 (a) A TEM image of a plant cell showing compartmentalised organelles: nucleus (orange), chloroplasts (green) and a round vacuole filled with sap on the upper right. Magnification ×15 000. (b) An SEM image of a single mitochondrion (coloured pink) in the cytoplasm of an intestinal epithelial cell. The mitochondrion has two membranes: an outer, surrounding membrane and an inner membrane that forms folds called cristae where chemical reactions occur. (c) An SEM image of two lysosomes in a pancreatic cell. Lysosomes (green) are small spherical vesicles bound by a single membrane (clearest on lower lysosome). Material probably representing partially digested cell organelles can be seen in each lysosome.

Inhibition of enzyme activity

Lysosomes are a type of vesicle. Vesicles are small sacs of fluid in the cytoplasm of a cell. They have single membranes surrounding them to contain enzymes that would otherwise start digesting the cell's own structures.

FIGURE 3.4.26 Grasses sprayed with glyphosate die within two weeks as a result of the repression of chlorophyll synthesis due to enzyme inhibition.

Enzyme activity can also be changed by inhibitor molecules that bind to the enzyme's active site, preventing the substrate from binding.

The inhibition of enzyme activity by an inhibitor molecule can be reversible or irreversible, depending on the strength of the bonds between the enzyme and inhibitor. Reversible inhibitors are used to control enzyme activity by switching them on or off. Many poisons are irreversible inhibitors, e.g. heavy metals such as lead and mercury, which bind permanently to the active sites of important enzymes. Scientists have used knowledge of irreversible inhibitors to manufacture pesticides that act on enzymes in the nervous system of insects, or herbicides that bind to enzymes involved in the photosynthesis pathway. For example, herbicides such as amitrole and glyphosate inhibit the production of chlorophyll, and paraquat and diquat block the light-dependent reactions in the first part of photosynthesis in green plants (Figure 3.4.26).

Enzyme inhibition is also classified as being competitive inhibition or **non-competitive inhibition**, depending on where the inhibiting molecule binds to the enzyme (Figure 3.4.27).

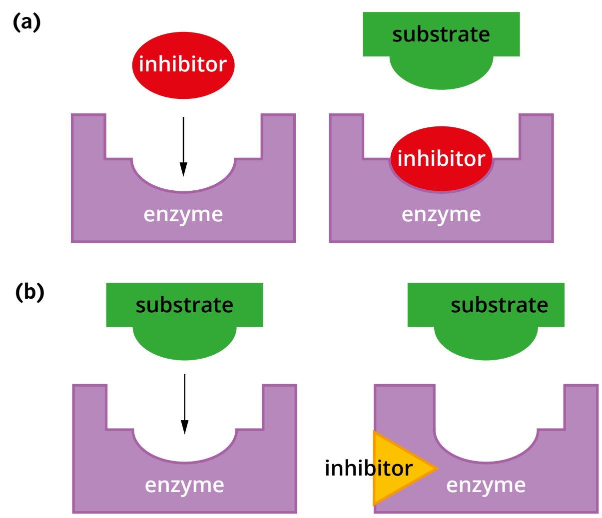


FIGURE 3.4.27 (a) Competitive inhibition involves an inhibitor molecule binding directly to the active site of the enzyme. The substrate is then unable to bind to the enzyme. (b) Non-competitive inhibition involves an inhibitor molecule binding to the enzyme in a position other than the active site. This changes the shape of the enzyme's active site, so that the substrate no longer fits.

Feedback inhibition occurs when a product that is produced late in a biochemical pathway is also an inhibitor of an enzyme earlier in the pathway. As the amount of the inhibiting product increases, the amount of enzyme molecules being inhibited also increases (Figure 3.4.28). This in turn reduces the amount of the inhibiting product. As the level of inhibiting product reduces, less of it will bind to the enzymes, allowing them to function again. Feedback inhibition is an important mechanism in controlling enzyme activity.

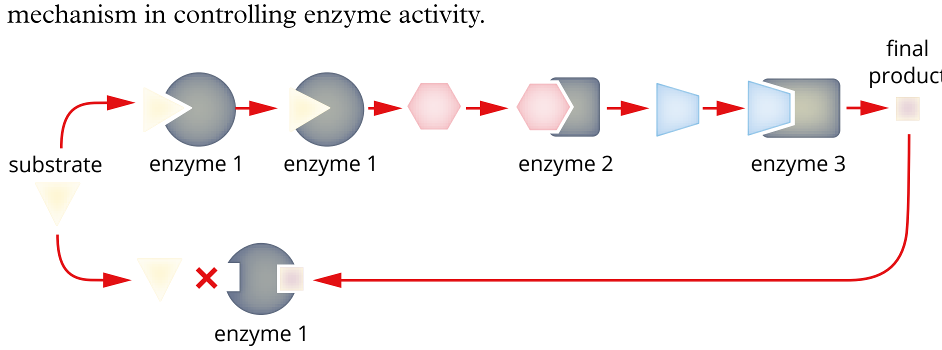


FIGURE 3.4.28 In feedback inhibition, when the amount of inhibiting product is high, enzyme activity is inhibited and the biochemical pathway slows. When the amount of inhibiting product is low, enzymes are not inhibited and the biochemical pathway accelerates.

Phosphorylation

The binding of a phosphate group to a protein is known as **phosphorylation**. The removal of a phosphate group from a protein is known as **dephosphorylation**. Phosphorylation is thought to be the most common regulatory mechanism of protein function, with as many as one-third of all proteins in the human body being substrates for phosphorylation at some point.

Phosphorylation and dephosphorylation both change the structure (or conformation) of proteins, and therefore both can regulate enzymes. For example, the phosphorylation of glycogen synthase inhibits its ability to interact with glucose. The phosphorylation of glycogen synthase is performed by another enzyme, called glycogen synthase kinase 3.

Cofactors and coenzymes

Some enzymes need additional components to enable them to catalyse a reaction. These components, called **cofactors**, bind to the enzyme. Cofactors can be inorganic ions such as iron (Fe^{2+}), magnesium (Mg^{2+}) and zinc (Zn^{2+}), or organic molecules such as proteins, vitamins and ATP.

Cofactor is the general name used for any extra ion or molecule that works with an enzyme.

Small, non-protein organic cofactors are known as **coenzymes** (Figure 3.4.29). For certain enzymes, a specific coenzyme is required to catalyse reactions. Often the coenzyme is structurally altered during the reaction, but afterwards reverts to its original form, which allows it to be reused. There are many types of coenzymes. They include vitamins, ATP, nicotinamide adenine dinucleotide (NADH), flavin adenine dinucleotide ($FADH^2$) and nicotinamide adenine dinucleotide phosphate (NADPH).

Except for vitamin C, all other vitamins must be modified in the body before they can function as coenzymes. An example is vitamin A, which is a coenzyme for the production of some proteins, such as the light-absorbing pigments in the retina of the human eye. The popular belief that eating carrots is good for night vision has substance, because the carrot's orange colour indicates the presence of vitamin A, which is used by the body to improve vision in low light.

Despite their name, coenzymes are not actually enzymes. They are molecules that work cooperatively with enzymes.

The vitamin B complex consists of eight vitamins that are used in the body to produce several coenzymes. Some examples are:

- B1 (thiamin), B2 (riboflavin) and B3 (niacin) work with enzymes in the conversion of glucose to energy (cellular respiration).
- B9 (folate) is needed to form red blood cells, and in fetal development for the nervous system, DNA synthesis and cell growth. Therefore, it is very important for pregnant women and has been related to prevention of spina bifida in babies.
- B12 is important for maintenance of myelin (the insulation around nerve cells) and in energy production. B9 and B12 operate together.

Controlling the availability of cofactors is another way for the body to regulate enzyme activity.

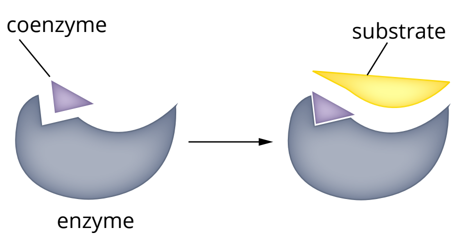


FIGURE 3.4.29 Coenzymes are non-protein organic cofactors that enable an enzyme to catalyse a reaction.

PA 1.5
PA 1.5
WS 1.7
WS 1.8

3.4 Review

SUMMARY

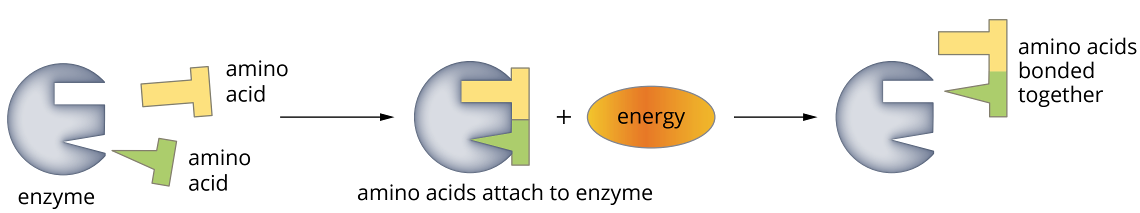
- Most enzymes are globular proteins that have a tertiary or quaternary three-dimensional structure that is vital for their function.
- Enzymes are:
  - usually specific to particular substrates, and therefore catalyse specific reactions
  - biological catalysts that have catalytic power to increase the rate of reactions by lowering the activation energy needed for reactions to occur.
- Activation energy is the amount of energy input required for a reaction to start.
- As enzymes do not form part of the product of the reaction they catalyse, they can be reused over and over again.
- The active site is a three-dimensional, pocket-like depression of the enzyme's structure that is shaped to interact with its specific substrate.
- When enzymes and substrates interact, they form an enzyme–substrate complex.
- There are two models of enzyme–substrate interaction.
  - The lock-and-key model states that the substrate fits exactly into the active site like a key fits into a lock.
  - The induced-fit model states that when a substrate binds to the active site of an enzyme, the active site can alter its shape to better fit the shape of the substrate.
- A biochemical pathway is a sequence of biochemical reactions catalysed by different enzymes, in which the product of each reaction becomes the substrate in the next reaction.
- Through enzyme regulation, a whole biochemical pathway can be regulated.
- Factors affecting the rate of enzymatic reactions include:
  - Temperature—high temperatures can alter an enzyme's three-dimensional structure and change the shape of the active site. This means the enzyme cannot act as a catalyst. This change is called denaturation.
  - pH—enzymes have an optimum pH range. If the enzyme is exposed to a pH outside its tolerances, the enzyme may become denatured.
  - Concentration—the concentrations of enzymes and their substrates will have an effect on the rate of a reaction, as both substrate and enzyme are required for the reaction to occur.
- Factors that determine whether enzymatic reactions can occur include inhibitors, phosphorylation, cofactors and coenzymes.
- Cofactors are additional components required by some enzymes to catalyse a reaction.
- Coenzymes are small, non-protein organic cofactors, such as vitamins, ATP, NADH and NADPH.
- Coenzymes are needed for reactions in biochemical pathways, including cellular respiration and photosynthesis.
- Controlling the availability of coenzymes is another way that biochemical pathways are regulated.

KEY QUESTIONS

1 State three main features of enzymes and explain their importance.

2 Describe the difference between the lock-and-key and induced-fit models of an enzyme–substrate interaction.

3 Does the following diagram showing an enzyme catalysing a reaction represent a catabolic or an anabolic reaction?



4 List examples of two enzymes and their substrates.

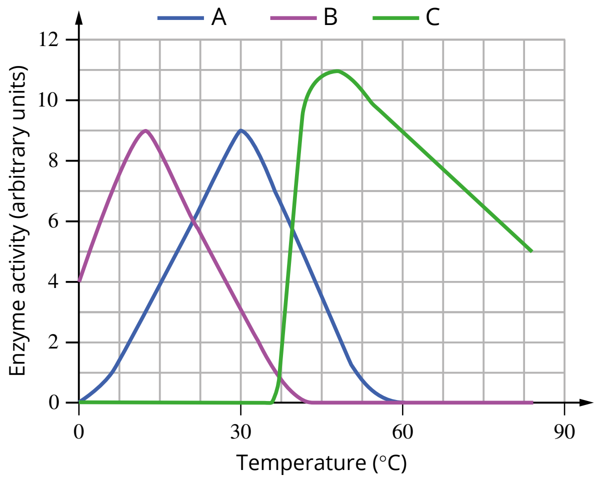
5 Pepsin is an enzyme that is released into the stomach of humans (pH 1.5–3.5, 37°C), where it breaks down proteins into polypeptides. Explain how you would expect the activity of pepsin to change as:

a the temperature is increased from 37°C to 45°C

b the pH is increased above 5.

6 An experiment was performed to investigate enzyme activity in three different species: the two-toed sloth (a mammal), an Arctic trout, and a bacterium from a thermal spring. The activities of the enzymes from each organism are plotted on the graph below.

Enzyme activity at different temperatures

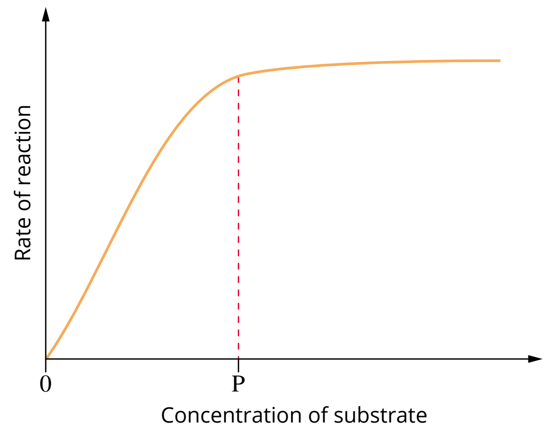


a Explain which line graph belongs to each animal.

b Why was no activity observed at 60°C for enzyme A?

7 The following graph illustrates the relationship between the concentration of an enzyme substrate and enzyme activity.

The effect of substrate concentration on the rate of a biochemical reaction



a Describe the relationship between the substrate concentration and the rate of reaction from 0 to P units of substrate concentration.

b Explain what happens at, and after, point P.

c The concentration of the enzyme is described as being a limiting factor. Explain what this means.

8 Explain what coenzymes are.

Chapter review

KEY TERMS

activation energy
active site
active transport
ADP (adenosine diphosphate)
aerobic respiration
amino acid
ammonia
anabolic
anaerobic respiration
ATP (adenosine triphosphate)
autotroph
bile
biochemical
carbohydrate
carbon dioxide
carbon fixation
carrier protein
catabolic
catalyse
catalyst
catalytic power
cell compartmentalisation
cell membrane
cellular respiration
channel protein
chlorophyll
chloroplast
cholesterol
coenzyme
cofactor
competitive inhibition
concentration gradient
consumer
cristae
denature
dephosphorylation
diffusion
disaccharide
egestion
endergonic
endocytosis
enzyme
enzyme–substrate complex
epithelium
excretion
exergonic
exocytosis
external environment
facilitated diffusion
feedback inhibition
fermentation
filtration
glucose
glycolysis
granum (pl. grana)
heterotroph
homeostatic
hydrophobic
hypertonic solution
hypotonic solution
inorganic compound
internal environment
isotonic solution
kidney
lactic acid
light compensation point
light-dependent reaction
light-independent reaction
limiting factor
lipid
liver
lumen
lysosome mesophyll
metabolic rate
metabolism
microvillus (pl. microvilli)
mineral
molecule
monosaccharide
nephron
nitrogen
nitrogenous waste
non-competitive inhibition
nucleic acid
nutrient
organic compound
osmoconformer
osmolarity
osmosis
osmotic gradient
osmotic pressure
oxygen
passive transport
pH
phagocytosis
phagosome
phospholipid
phosphorylation
photolysis
photosynthesis
pinocytosis
polypeptide
polysaccharide
producer
proteasome
protein
pseudopodia
pyruvate
reabsorption
reaction
receptor-mediated endocytosis
receptor
root hair
saphrotroph
secretion
semipermeable membrane
simple diffusion
solute
solvent
specificity
stroma
substrate
surface-area-to-volume ratio
thylakoid
urea
uric acid
urine
vascular plant
vesicle
vitamin
waste
water

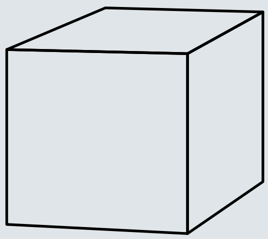
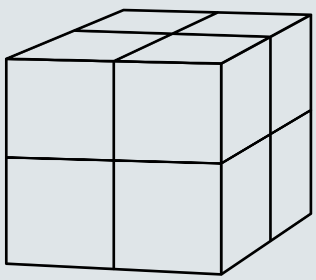
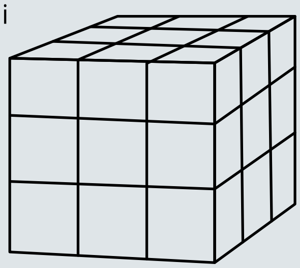
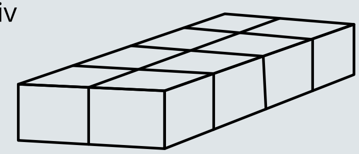
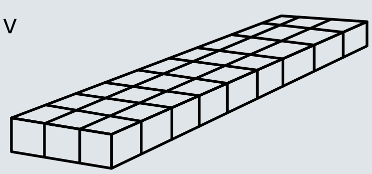
REVIEW QUESTIONS

1 Osmosis is a special kind of diffusion. Write a definition for osmosis. Use a diagram to illustrate your answer.

2 Distinguish between simple diffusion and osmosis.

3 Distinguish between facilitated diffusion and active transport in the movement of substances.

4 a Complete the table on the next page by filling in the surface-area-to-volume (SA:V) ratios. Show your working.
b What happens to the SA:V ratio as objects increase in size, as occurs in examples (i), (ii) and (iii) in the table?
c In the table, objects (ii) and (iv) have the same volume; so do objects (iii) and (v). How does a change in shape affect the SA:V ratio of these objects?
d Explain the significance of the SA:V ratio for organisms and/or exchange organs.

Object	Surface area	Volume	SA : V ratio
i 		1 cm × 1 cm × 1 cm = 1 cm^3	
ii 	4 cm^2 × 6 sides = 24 cm^2		
iii 			
iv 			
v 			

5 Outline how vesicles are used to transport materials secreted by a cell.

6 Outline the process of endocytosis.

7 Which of the following is a feature of exocytosis but not endocytosis?

A changes in the shape of the cell membrane

B formation of vesicles

C use of ATP

D secretion

8 Distinguish between autotrophs and heterotrophs.

9 Copy and complete the following table, which should list the four main types of organic compounds that make up organisms, the elements of which each is composed, and the main function of each compound.

Organic compound	Elements	Main function
1		
2		
3		
4	Carbon, hydrogen, oxygen, phosphorus, nitrogen	

10 Name the units that make up the following compounds:

a nucleic acids
b proteins
c carbohydrates

11 Are minerals and vitamins inorganic or organic? Explain your answer.

12 Briefly describe what happens to pyruvate in the two processes that can occur after glycolysis when:

a oxygen is present
b oxygen is absent.

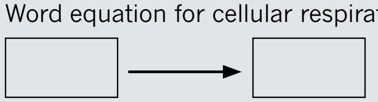
13 The following statements can be used to write a word equation for photosynthesis and cellular respiration.

P carbon dioxide and water
Q carbon dioxide, water and energy
R solar energy and chlorophyll
S glucose and oxygen

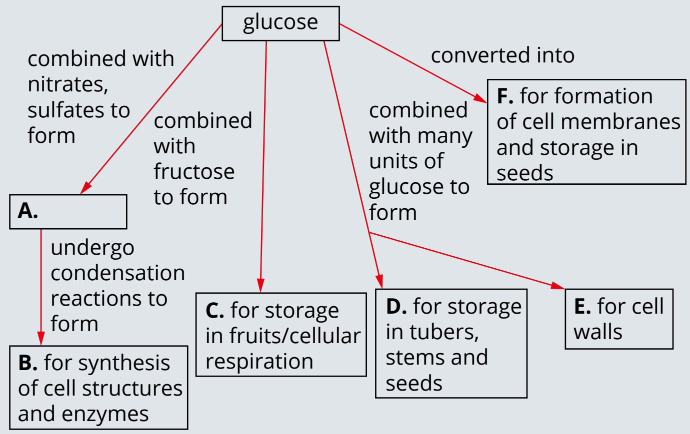
Complete the word equation for photosynthesis and cellular aerobic respiration using the shorthand form (P, Q, R or S) of the statements provided.

Word equation for photosynthesis:

Word equation for cellular respiration:

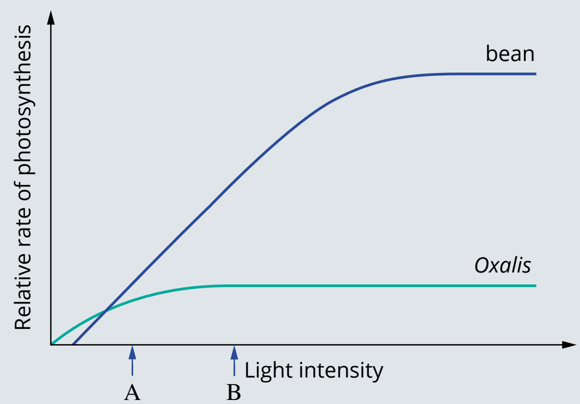


14 The figure below is a summary of the major processes that occur after photosynthesis. State the correct term for each of the letters A, B, C, D, E and F.



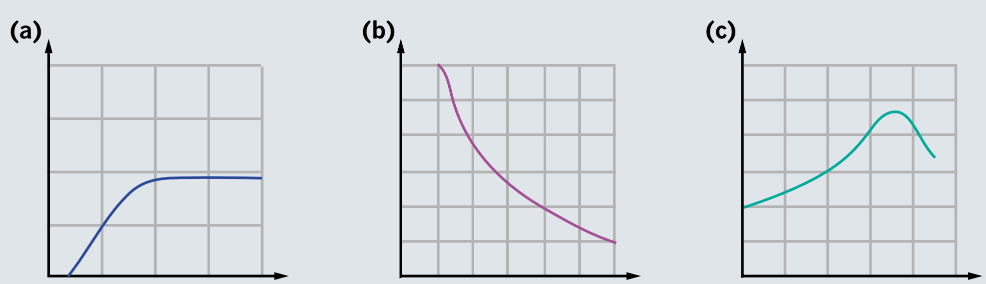
15 The following graph shows the rate of photosynthesis in a bean plant, adapted to high light intensity, and an oxalis plant, adapted to low light intensity.

The effect of light intensity on the rate of photosynthesis in a bean plant and an oxalis plant



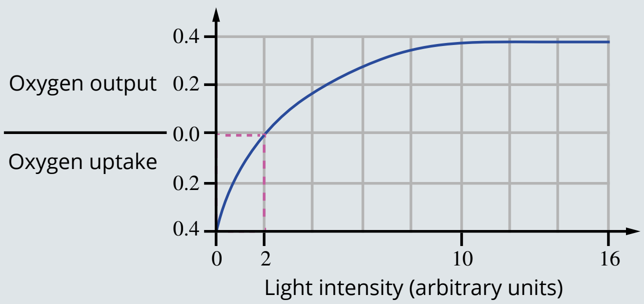
a What is the limiting factor at point A for each plant?
b What is the limiting factor at point B for each plant?

16 The following graphs represent the changes in rate of photosynthesis when temperature, light intensity or distance from light source are increased. Label each graph with its correct factor.



17 The following graph shows the relationship between net oxygen uptake or output and light intensity for a green plant.

The effect of light intensity on the output and uptake of oxygen by a green plant



Explain what is happening when light intensity is at:

a 2 units

b 16 units.

18 The Australian hopping mouse, *Notomys alexis*, can survive without drinking water. Use the data in the table below to explain this remarkable adaptation.

Path for water loss/gain	Volume of water (mL/day)
GAIN	
drinking	0.0
food	0.7
metabolic production	0.9
TOTAL	1.6
LOSS	
evaporation	1.21
urine	0.33
faeces	0.06
TOTAL	1.6
NET LOSS/GAIN	0

19 The table below shows the relative concentrations of urea, glucose, amino acids, salts and proteins in the primary filtrate and urine of mammals as a percentage of the concentration in blood plasma.

Substance	Primary filtrate (%)	Urine (%)
Urea	100	700
Glucose	100	0
Amino acids	100	0
Salts	100	200
Protein	0	0

a What is the explanation for each value, for both primary filtrate and urine?

b Suggest how the values would be different in persons suffering from diabetes, or from kidney damage due to a heavy blow.

20 Enzymes reduce the activation energy of a reaction by:

A bringing the reactants close together so that a reaction is more likely to occur

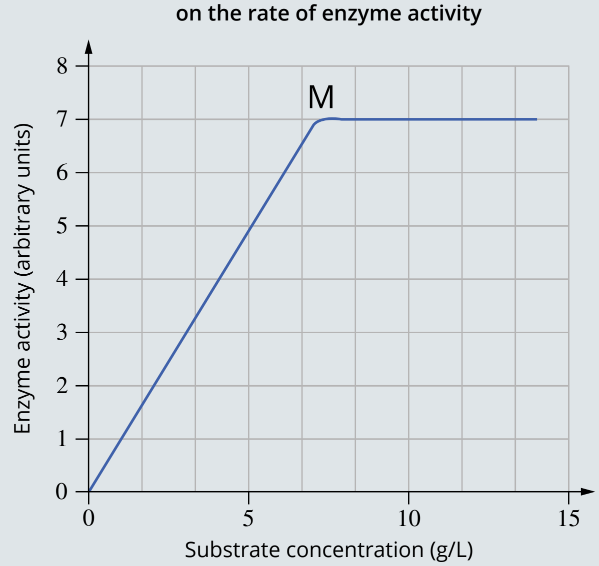
B orientating the reactants in the most favourable position for the reaction

C providing a micro-environment favourable to the chemical reaction

D all of the above.

21 A student investigating the activity of the enzyme pepsin, which is found in the stomach of humans, observed the change in enzyme activity as the concentration of the substrate (protein) increased. The experiment was conducted at pH 3 and 37°C. The student's data is presented in the graph below.

The effect of substrate concentration on the rate of enzyme activity



The student wanted to change the experiment so that the rate of reaction at point M was higher than that shown. To do this, the student could:

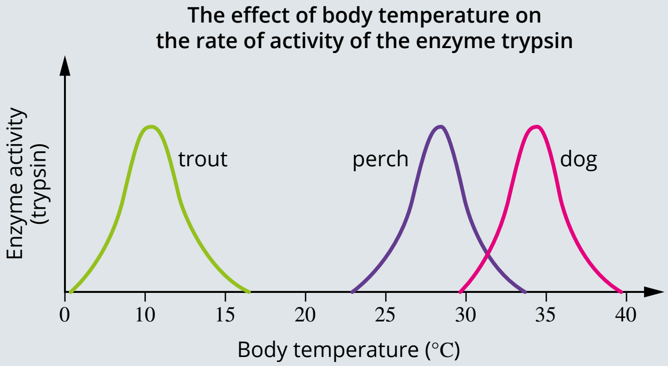
A increase the pH to 8

B decrease the temperature

C increase the amount of enzyme

D increase the concentration of the substrate.

22 Trypsin is a digestive enzyme secreted by the pancreas of vertebrate animals. A biologist studying enzyme activity isolated trypsin from a mammal and two different species of fish, and tested the enzyme activity at different temperatures. The experimental results are illustrated in the graph.



a Define 'optimum temperature of an enzyme'.

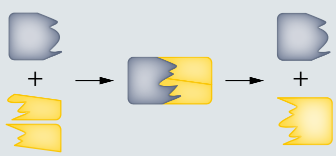
b What is the optimum temperature for trypsin in the:
i trout? **ii** perch? **iii** dog?

c Describe what happens to the activity of trypsin after 10°C in the trout, 28°C in the perch and 34°C in the dog. Explain why this occurs.

d Fish are ectotherms. Suggest a reason for the difference in the optimal temperatures of the enzyme in trout and perch.

23 Pyridazinone herbicides are used in agriculture to reduce the number of pest plant species. Pyridazinone herbicides inhibit enzymes found in the light-dependent stage of photosynthesis. Explain how pyridazinone herbicides might act on a pest plant.

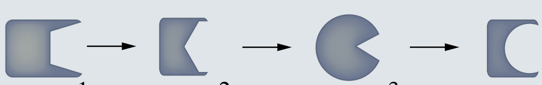
24 The following diagram illustrates one model of enzyme activity.



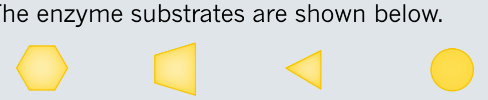
a Explain which of the two models of enzyme activity is being illustrated.

b Explain how this model of enzyme activity could be used to explain how some enzymes can act on multiple substrates.

25 Many chemical reactions in living things occur as part of a metabolic pathway. Metabolic pathways involve a series of reactions, with a different enzyme catalysing each step in the pathway. In these pathways, the product of one reaction is the substrate for the next reaction. The diagram below shows the enzymes involved in one such pathway.



The enzyme substrates are shown below.



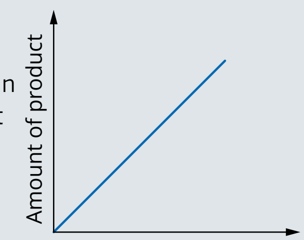
a **i** Match each substrate with its enzyme.
ii What was basis of your decision?

b The following molecule is the final product of the reaction.

i If the concentration of the final product builds up in the cell, the reaction will stop. Explain how the increase in the concentration of the final product stops the reaction proceeding.

ii Is the product acting as a competitive inhibitor or a non-competitive inhibitor? Explain your answer.

26 Consider the following incomplete graph for an enzyme-controlled reaction in which the enzyme is present at concentration x. Assume there is a fixed amount of substrate present.



a Eventually, the shape of the graph will change. Continue the line graph according to your expectations and explain what happens.

b Redraw the graph for an enzyme concentration of 2x.

27 Bacteria live in a vast range of different environments. Conditions range from the ice sheets of Antarctica to the superheated water surrounding the undersea volcanoes of the mid-ocean ridges, or the hot springs of Yellowstone. Bacteria living in the Antarctic ice are called cryophiles, while those living in water at close to boiling point are hyperthermophiles. An example of a cryophilic bacterium is *Psychrobacter*, which thrives at temperatures between –10 and 42°C. *Methanopyrus* is a hyperthermophilic bacterium. It has been shown to survive and reproduce at temperatures between 84 and 110°C. Despite their extreme lifestyles, these bacteria—like all living things—use proteins in the form of enzymes to regulate their metabolism. An experiment was performed using both of these groups of bacteria. Cultures of *Psychrobacter* and *Methanopyrus* were incubated at a temperature of 60°C for three hours. The bacterial cultures were then returned to their optimal temperature and the growth of the bacteria in each culture was monitored.

a What is meant by the optimal temperature for a protein?

b **i** Which of the cultures, if any, would you expect to show growth?
ii Explain your reasoning.

28 After completing the Biology Inquiry on page 152, reflect on the inquiry question: How do cells coordinate activities within their internal environment and the external environment? Using at least five key terms from this chapter, describe three ways in which cells control the materials that move across the cell membrane.

MODULE 1 • REVIEW

REVIEW QUESTIONS

Cells as the basis of life

WS 1.9 WS 1.10 MR 1

Multiple choice

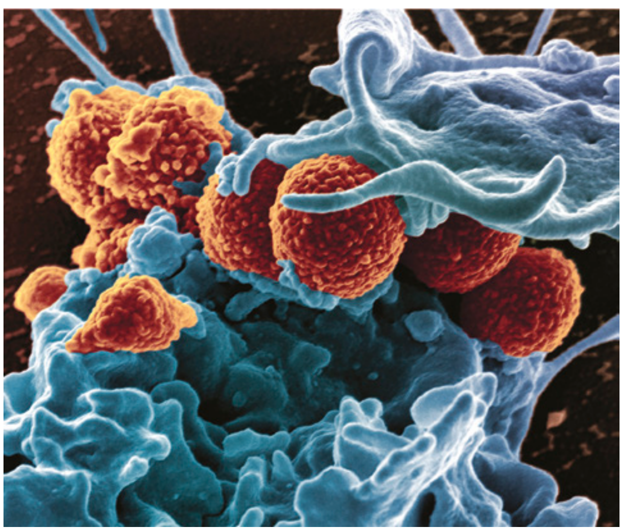
1 A student observes and draws an amoeba to scale. The length of the drawing is 100 mm. The actual length of the amoeba is 100 µm. What is the magnification of the drawing?

A ×0.001
B ×1
C ×100
D ×1000

2 Which of the following would not be visible using a light microscope?

A nucleus
B chloroplast
C vacuole
D ribosome

3 The image below shows *Staphylococcus aureus* cells (bacteria commonly called 'golden staph') being engulfed by a white blood cell. The cocci (round bacterial cells) are coloured orange in this image to represent their actual colour. Identify the type of microscope that was used to produce this image.



A A confocal microscope used laser light sections to produce a 3D image.
B A light microscope and computer program were used to create a fluorescent light micrograph (LM).
C A transmission electron microscope (TEM) was used to look at a thin section at very high resolution.
D A scanning electron microscope (SEM) was used to look at surface features of whole cell specimens.

4 Which list contains names used to classify different types of cells?

A plant, animal, virus, ribosome
B prokaryote, eukaryote, plant, animal
C TEM, SEM, ATP, ADP
D prokaryote, virus, archaea, fungi

5 Which of the following features distinguishes archaea from bacteria?

A the structure of lipids in the cell membrane
B the presence of a nucleus
C the presence of membrane-bound organelles
D the presence of a cell wall

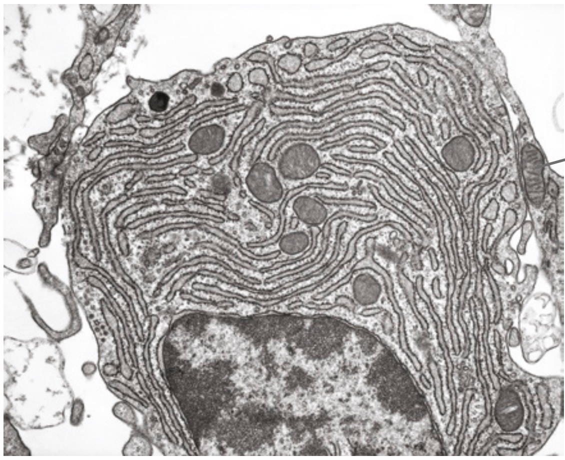
6 Which of the following is an example of a eukaryotic cell?

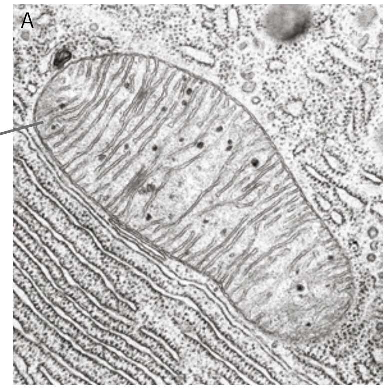
A a fungal cell
B a bacterium
C an enzyme
D a virus

7 Which of the following lists contains organelles that are found in both animal and plant cells?

A mitochondria, nuclei and chloroplasts
B mitochondria, Golgi apparatus and chloroplasts
C ribosomes, chloroplasts and nuclei
D mitochondria, Golgi apparatus and nuclei

8 Identify organelle A in the electron micrograph below.





A mitochondrion
B rough endoplasmic reticulum
C nucleus
D vacuole

9 Select the statement that best describes the cell membrane.

A a single layer of molecules that acts like a fluid
B a membrane with pores that open and close to actively transport substances in and out of a cell
C a lipid bilayer that is semipermeable to organic molecules and ions
D a viscous protective coating of oil around each cell

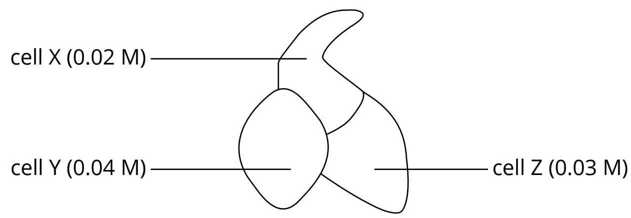
10 A student was interested in the actions of phospholipid molecules and how they act in environments that are different from the cellular environment (where they form cell membranes). The student performed an experiment to test this, adding phospholipids to a test-tube containing water. Which of the following is the expected result?

A The phospholipids would dissolve in the water.
B The phospholipids would line up in single file on the surface of the water with the heads pointing into the water.
C The phospholipids would form a bilayer with the heads pointing inwards and the tails pointing outwards.
D The phospholipids would form a bilayer with the heads pointing outwards and the tails pointing inwards.

11 Which of the following is required for osmosis to occur?

A a fully permeable membrane
B a semipermeable membrane
C ATP
D an enzyme

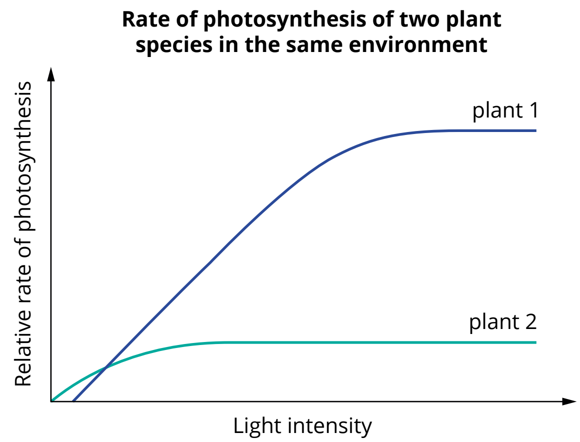
12 Three cells (X, Y and Z) containing different solute concentrations were placed next to each other, as shown in the following diagram. (M is molar concentration, a measure of solute concentration. A higher value means a higher solute concentration.)



In which direction will osmosis occur?

A from X to Y only
B from X to Y, X to Z and Z to Y
C from Y to Z only
D from Y to Z and Z to X

13 The graph below shows the rate of photosynthesis of two different plant species experiencing the same environmental conditions.



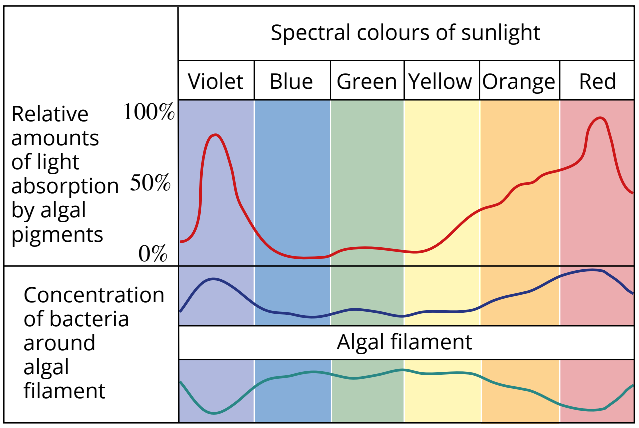
Which limiting factor is most likely to be causing the difference in photosynthetic rates between the two plants?

A oxygen availability
B chloroplast availability
C carbon dioxide availability
D water availability

14 Which of the following statements about cellular respiration in plants is true?

A it occurs only at night
B it occurs only in green leaves
C it occurs independently of photosynthesis
D it requires energy from sunlight

15 In an experiment, a photosynthetic algal filament was placed in a solution containing aerobic bacteria. The filament was then exposed to different spectral light colours along its length. The following diagram indicates the distribution of bacteria around the algal filament after one hour.



What does the distribution of bacteria indicate about the relationship between spectral light colour and the rate of photosynthesis?

A The rate of photosynthesis is highest at the spectral band of green, followed by yellow and then orange.
B The rate of photosynthesis is highest at the spectral band of red, followed by violet and then orange.
C The rate of photosynthesis is evenly distributed across the spectral colours.
D All the spectral light colours are used for photosynthesis.

16 A student performed an investigation to model the semipermeable nature of a cell membrane. She placed distilled water in two bags made from dialysis tubing. (The pores of dialysis tubing are smaller than starch molecules.) She then weighed the bags and recorded their masses. Next, the student placed one of the bags (bag A) in a beaker of distilled water. She placed the second bag (bag B) in a beaker containing 10% w/v solution of starch. After one hour, the student weighed the bags again.

What is the dependent variable in this experiment?

A the % concentration of starch
B the size of the bags
C the volume of distilled water
D the mass of the bags in grams

17 Predict the likely outcome for the student's results in Question 16.

A The mass of bag A would decrease over time.
B The mass of bag A would increase over time.
C The mass of bag B would decrease over time.
D The mass of bag B would increase over time.

18 Identify the most accurate description of ATP.

A amino triphosphate
B an energy storage molecule
C the main product of photosynthesis
D aerobic transport pathway

19 Compared with heterotrophs, the cells of autotrophs produce almost no true waste. What is the explanation for this?

A Autotrophs have a much lower metabolic rate.
B Autotrophs recycle all nutrients.
C Autotrophs prevent loss of water.
D Autotrophs are unable to produce a nitrogen waste product.

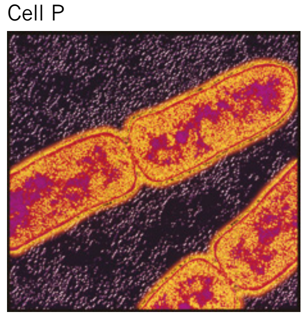
20 An organic molecule required by an enzyme for functioning is best described as:

A an enzyme–substrate complex
B a coenzyme
C an active site
D an inhibitor molecule

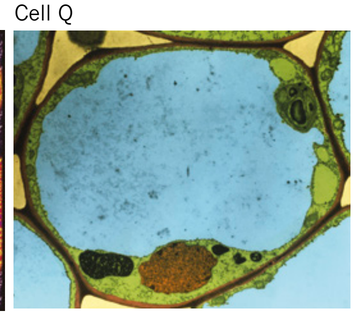
Short answer

21 The following images show the transmission electron micrographs of two cells, P and Q.

Cell P



Cell Q



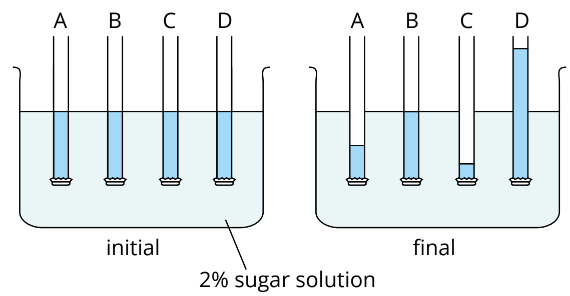
a Which of the images shows a prokaryote? Give reasons for your answer.
b On each figure, draw an arrow and label the structures where DNA can be found.
c Identify two structures in cell Q that are not visible in cell P.

MODULE 1 • REVIEW

22 Complete the following table of cell organelles and their functions.

Organelle	Found in	Function
	all eukaryotic cells	contains DNA with genetic instructions for cell
chloroplast	eukaryotic plant cells	
ribosome		polypeptide synthesis
vacuole	eukaryotic cells—many small vacuoles in animal cells; single large vacuole in plant cells	
cell membrane		regulates transport of substances in and out of cell

23 The diagram below shows four tubes containing solutions with different concentrations of sugar. One end of each tube is covered by a semipermeable membrane. The tubes are placed in a tank containing a 2% sugar solution (initial) and are left in the tank for an hour (final). The results of the initial and final fluid levels in the tubes are shown in the diagram. What were the original concentrations of solutions A, B, C and D? Explain your reasoning.



24 Root hair cells on the roots of plants use energy to take up some nutrients from the soil, but not others. Describe the circumstances in which energy is expended during nutrient uptake.

25 **a** Write the word equation for photosynthesis.

b Identify the organelle in which photosynthesis takes place.

c Outline how oxygen is produced during the process of photosynthesis.

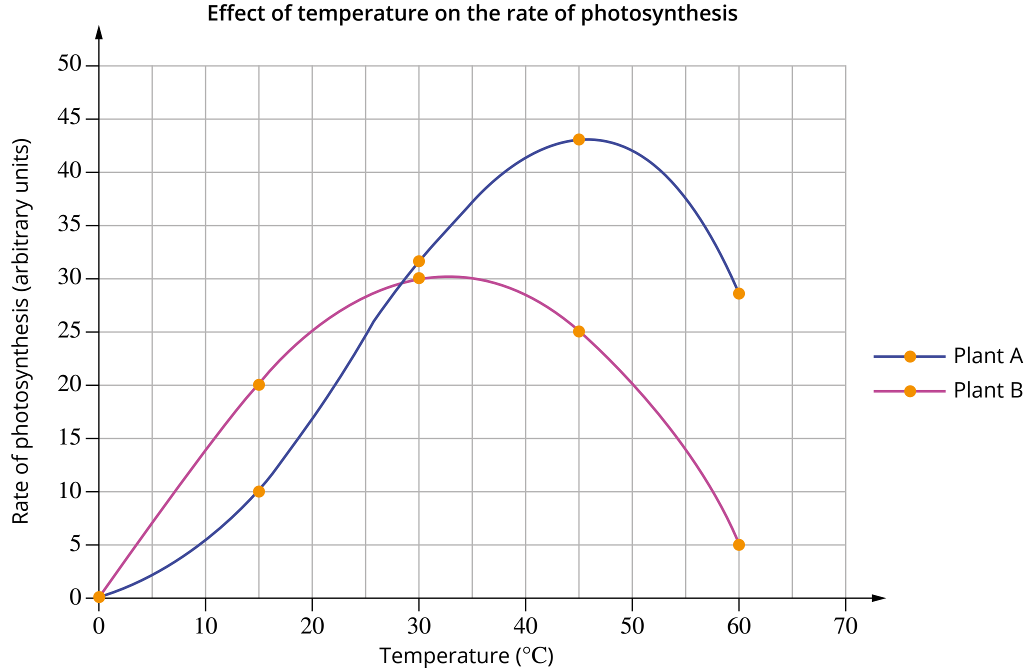
26 Scientists investigated the effect of temperature on the rate of photosynthesis on two different plants, plant A and plant B. The graph shows the results of the experiment.

a Compare the effect of temperature on the rate of photosynthesis on plant A and plant B.

b Explain why the rate of photosynthesis falls beyond 50°C.

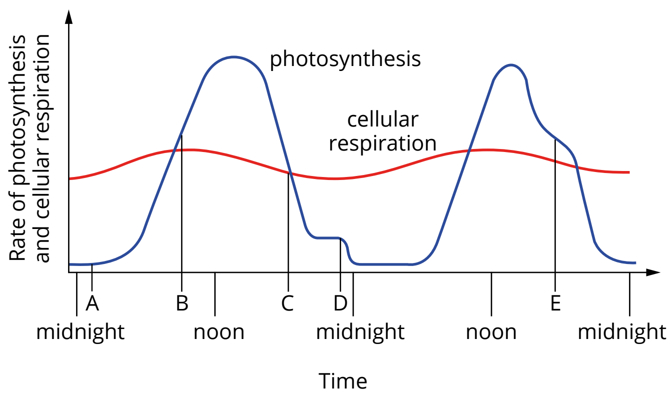
c Which plant is more suited to a desert environment? Justify your answer.

Effect of temperature on the rate of photosynthesis



27 The following graph shows the rates of photosynthesis and cellular respiration in an indoor plant that receives plenty of natural light through a large window.

Rates of photosynthesis and cellular respiration in an indoor plant at different times

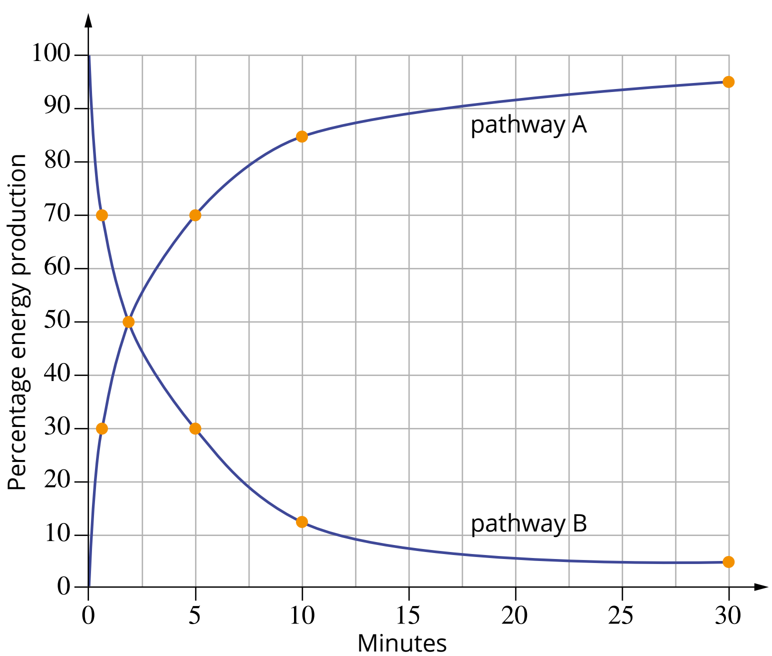


a Deduce whether there is a net oxygen uptake or output at each of these times: A, B, C, D, E.

b Propose what change in the plant's environment might have caused the rate of photosynthesis shown at times D and E.

28 The graph below shows the contributions of the two energy-producing pathways (aerobic and anaerobic respiration) to physical activity.

Energy produced using aerobic and anaerobic respiration



a Athletes competing in sports that require short-term power output, such as sprinting, obtain most of their ATP from the anaerobic pathway, but athletes requiring sustained energy use aerobic respiration to meet most of their energy needs.

i Why do muscle cells need ATP?

ii What is the name of the process that produces ATP during anaerobic respiration?

iii Explain which pathway (A or B) is most likely to represent ATP production by a sprinter.

iv Why can't anaerobic respiration supply the energy needs of athletes in events requiring energy over a sustained period of time?

b Lactic acid is produced during anaerobic respiration. What happens to this lactic acid?

c Animals make lactic acid during anaerobic respiration, but yeasts and plants produce ethanol and CO_2. Suggest a reason why the products are different in animals and plants.

29 The following diagram represents a nephron from a mammalian kidney.

a Recall the function of a kidney in the excretory system.

b Distinguish at least two differences that would be expected between the fluid at locations X and Y in a healthy person.

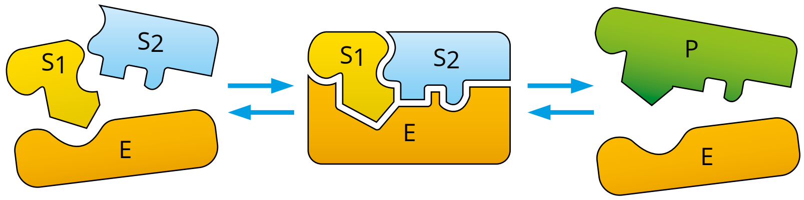
c Account for these differences.

30 Enzymes are used to catalyse cellular reactions.

a Which enzyme activation model does the diagram (right) represent?

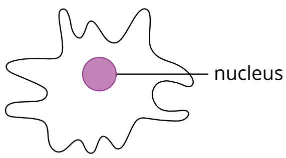
b If heated above its critical temperature, an enzyme denatures. Define ‘denature’.

c How does this affect the enzyme’s activity?

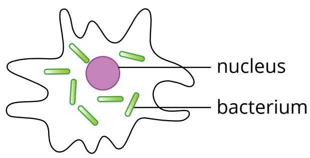


Extended response

31 *Amoeba proteus* is a unicellular member of the kingdom Protista. It is frequently infected with bacteria.



Amoeba proteus without bacteria

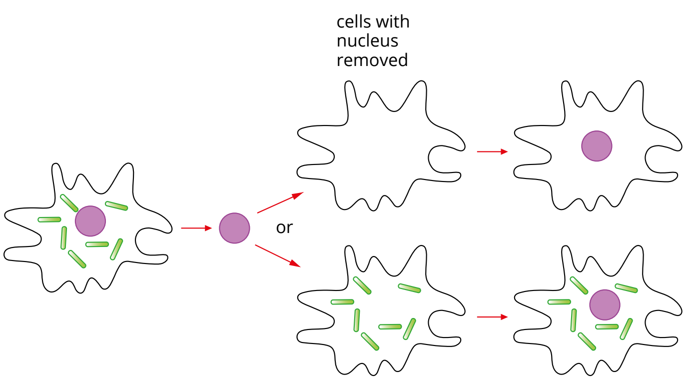


Amoeba proteus with bacteria

a To which domain of life does *Amoeba proteus* belong?

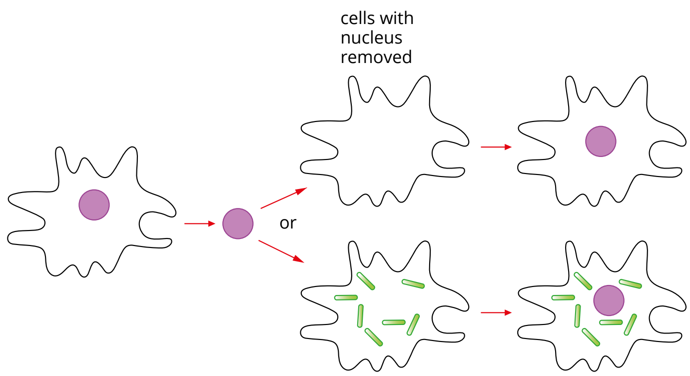
b Describe how something as large as a bacterium would have entered *Amoeba proteus*.

c In one experiment, the nucleus was removed from a number of infected cells and transferred to other *Amoeba proteus* cells that had had their nucleus removed (enucleated). Some of the receiving cells had bacteria and others did not.



The *Amoeba proteus* cells were then provided with all the nutrients they needed. The nuclei transplanted from a bacteria-infected cell to a non-bacteria-infected cell did not survive. The nuclei transplanted from a bacteria-infected cell to a bacteria-infected cell survived. What conclusion can be drawn from this experiment?

d As part of the experiment, nuclei were taken from *Amoeba proteus* that had not been infected with the bacteria and transplanted into enucleated cells with and without bacteria.



Most of the cells, both with and without the bacteria, survived.

i What conclusion can be drawn from this experiment?

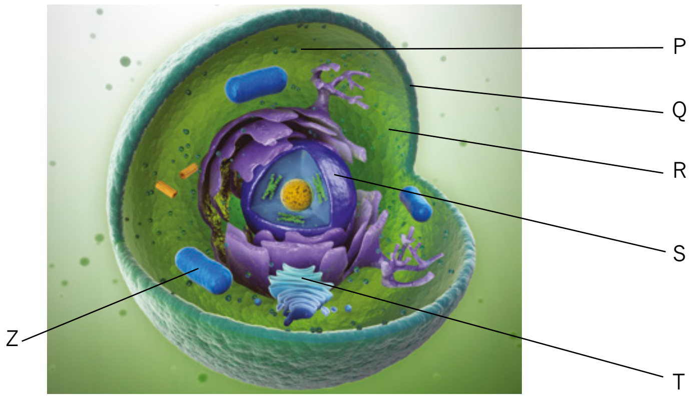
ii Why was it necessary to perform this second experiment?

e Further research showed that the *Amoeba proteus* infected with the bacteria were unable to produce an enzyme that uninfected *Amoeba proteus* were still able to produce. It was shown that the bacteria were producing the enzyme being used by the infected *Amoeba proteus*.

i How does this experiment support the theory that mitochondria and chloroplasts are the result of endosymbiosis? (refer to Chapter 2, Additional content, page 85 to complete the answer)

ii Outline two other pieces of evidence that support the theory that chloroplasts and mitochondria became organelles as a result of endosymbiosis.

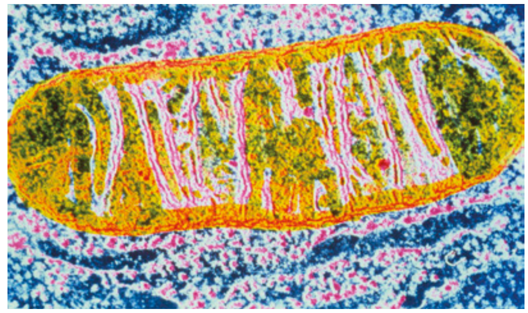
32 The following is a three-dimensional image of an animal cell.



a Identify structures P, Q, R, S and T.

b What is a key feature of structure Q? How does this feature relate to its function?

A transmission electron micrograph of structure Z is shown in the following figure. Structure Z is where most aerobic respiration occurs.



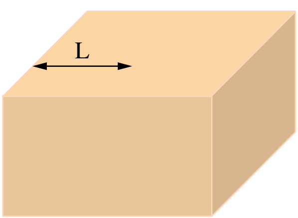
c Identify structure Z.

d Write the word equation for aerobic respiration.

e Structure Z requires oxygen to carry out aerobic respiration. Explain how oxygen from the blood eventually enters structure Z.

---

33 To investigate the effect of surface-area-to-volume ratio on the rate of diffusion, a student prepared different-sized agar cubes containing phenolphthalein. The agar cubes were then suspended in a 4% sodium hydroxide solution for 10 minutes. When sodium hydroxide diffuses into the agar, the agar turns pink. After 10 minutes, the agar cubes were cut in half and the length of the colourless area (L) was measured. The diagram shows a cross-section of an agar cube.



The following table shows the results of the experiment.

Length of cube side (cm)	Surface area of cube (cm^2)	Volume of cube (cm^3)	Surface-area-to-volume ratio of cube (SA:V)	Length of colourless area, L (cm)	Volume of colourless area (L × L × L) (cm^3)	Percentage diffusion (%)
1.0				0.0		
1.5				0.4		
2.0				0.8		
2.5				1.8		

Surface area of cube = 6 × (length of cube × length of cube)

Volume of cube = length of cube × length of cube × length of cube

$$\text{surface-area-to-volume ratio of cube} = \frac{\text{surface area of cube}}{\text{volume of cube}}$$

$$\text{Percentage diffusion} = \frac{(\text{volume of cube} - \text{volume of colourless area})}{\text{volume of cube}} \times 100$$

a Calculate the volume, surface area, surface-area-to-volume ratio, and percentage diffusion of each cube, and complete the table.

b Use graph paper to plot a graph of percentage diffusion against surface-area-to-volume ratio. Include a best fit curve in the graph.

c Using the graph you plotted in part b, describe the relationship between surface-area-to-volume ratio and diffusion in an agar cube.

d Which size cube was the most effective for maximising diffusion?

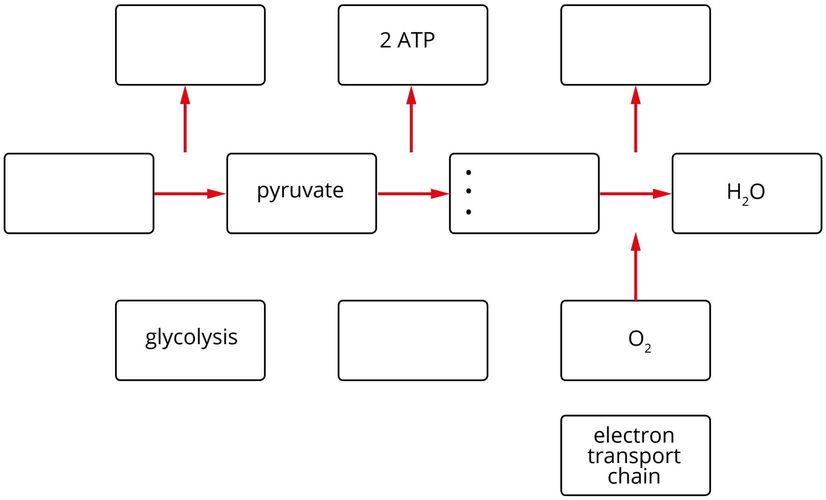
e Propose an explanation for your answer to Question d.

f A large surface area is essential for quicker diffusion into the cell. Using the results from the experiment, explain why there is a limit to the size individual cells can grow.

g Suggest how the reliability and validity of this experiment can be improved.

34 Aerobic respiration is a process that is essential for the survival of most life forms. The diagram below shows the stages of aerobic (cellular) respiration and the inputs and outputs of each stage.

a Complete the diagram by filling in the empty boxes.



b DNP (2,4-dinitrophenol) is a chemical that was used during World War I to make explosives. It was noticed that the workers handling the DNP had extremely high body temperatures (up to 44°C) and suffered from severe weight loss. Some workers died as a result of absorbing DNP through their skin, ingesting it or inhaling it. Research into DNP has shown that one of its actions is to block the movement of phosphate ions into the mitochondria.

i Normally, during aerobic respiration much of the energy released from the breakdown of glucose is used to build ATP. What happens to the rest of the energy?

ii Suggest how the action of DNP could lead to the very high body temperatures observed.

iii The very high body temperatures have been associated with a number of fatalities. Explain how high body temperatures can lead to cell death.

c Why would ingestion of DNP lead to weight loss?

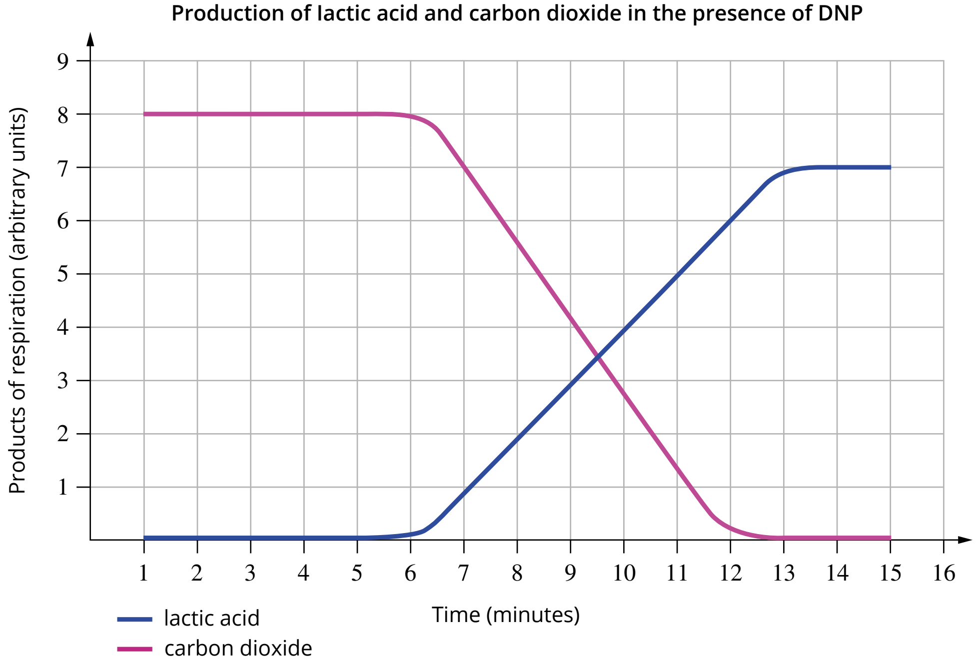
d A student was investigating the effects of DNP on cellular respiration. A cell culture was supplied with glucose and monitored for the products of respiration. Part-way through the experiment, DNP was added to the culture. The graph below shows the results of the experiment.

i At what time was the DNP added to the culture? How do you know?

ii Why is lactic acid being produced by the cells?

iii DNP is highly toxic. Describe two safety precautions that the student should implement while performing this experiment.

Production of lactic acid and carbon dioxide in the presence of DNP



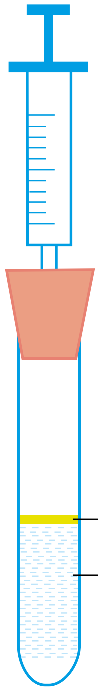
35 A student investigated the effect of varying types of sugar solutions (glucose, lactose, fructose, maltose and sucrose) on the rate of anaerobic respiration in yeast. The student hypothesised that the rate of respiration in yeast will be the highest for glucose. The steps in the experiment are described below.

Step 1: 10 mL of fructose solution (25% concentration), 5 mL of yeast suspension (10% concentration) and three drops of paraffin oil were added to a test-tube and mixed thoroughly.

Step 2: The test-tube was sealed with a rubber stopper with a syringe attached, as shown in the diagram at right.

Step 3: After 15 minutes, the volume of gas collected in the syringe was recorded.

Step 4: Steps 1 to 3 were repeated four more times. The experiment was then repeated using four other sugars: glucose, lactose, maltose and sucrose. The results are shown in the table to the right.



Sugar	Set 1	Set 2	Set 3	Set 4	Set 5	Mean
fructose	1.4	1.4	2.0	2.6	5.4	
glucose	9.0	8.2	7.0	8.6	8.8	
lactose	0.0	0.0	0.0	0.0	0.0	
maltose	2.8	3.2	3.0	3.0	6.2	
sucrose	7.4	7.0	7.0	6.6	6.8	

a Define anaerobic respiration.

b Write the word equation for the anaerobic respiration of yeast.

c Explain the purpose of the paraffin oil in this experiment.

d Calculate the mean for the experimental results and complete the table.

e Using a suitable graph paper or software, plot the volume of gas produced against type of sugar.

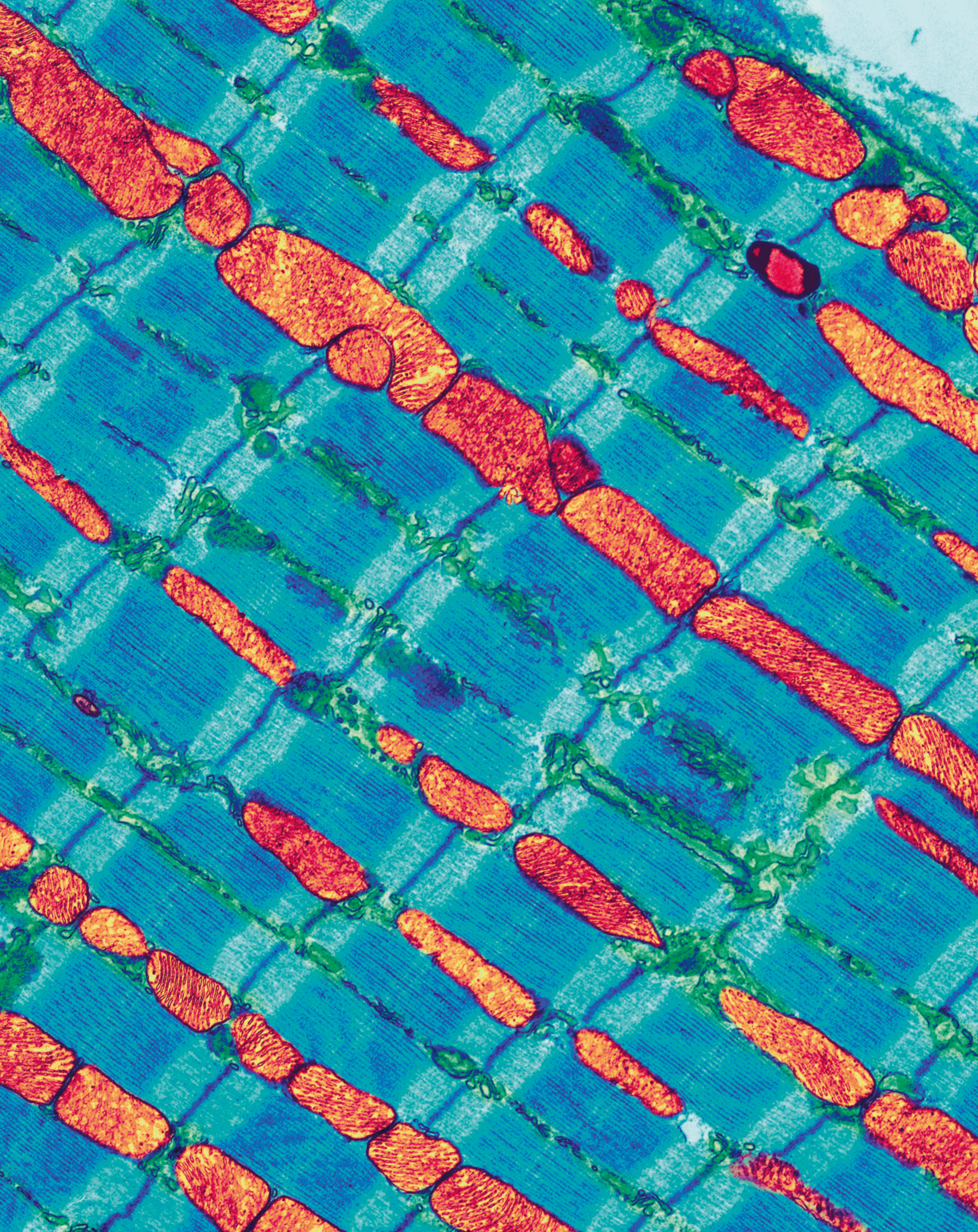
f Which type of sugar resulted in the:

i highest rate of respiration?

ii lowest rate of respiration?

g Was the student's hypothesis supported by the experimental results?

h Suggest a suitable control for the experiment.



MODULE 2

Organisation of living things

Multicellular organisms typically consist of a number of interdependent transport systems that range in complexity and allow the organism to exchange nutrients, gases and wastes between the internal and external environments.

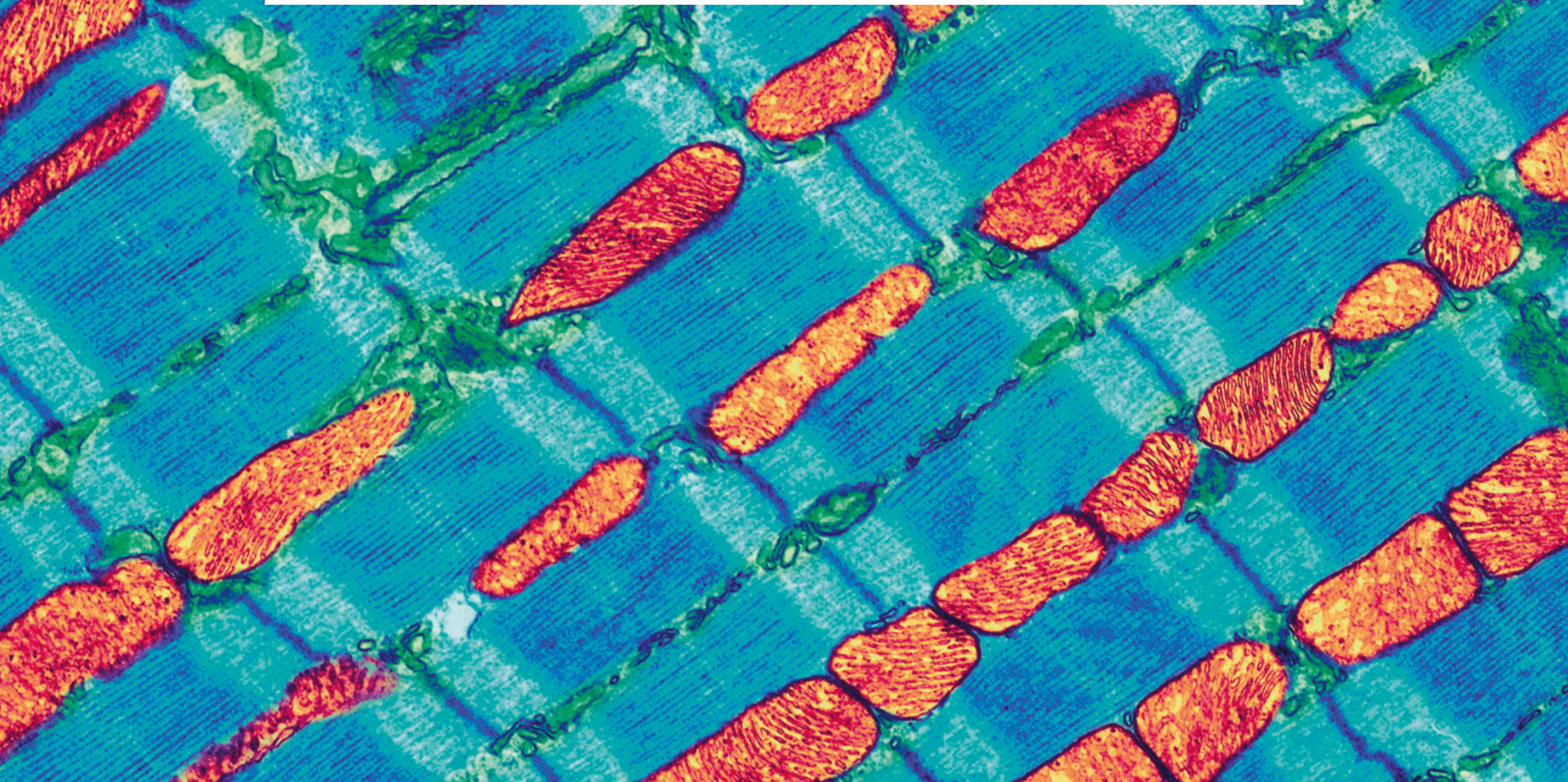
Models of transport systems and structures have been developed over time, based on evidence gathered from a variety of disciplines. The interrelatedness of these transport systems is critical in maintaining health and in solving problems related to sustainability in agriculture and ecology.

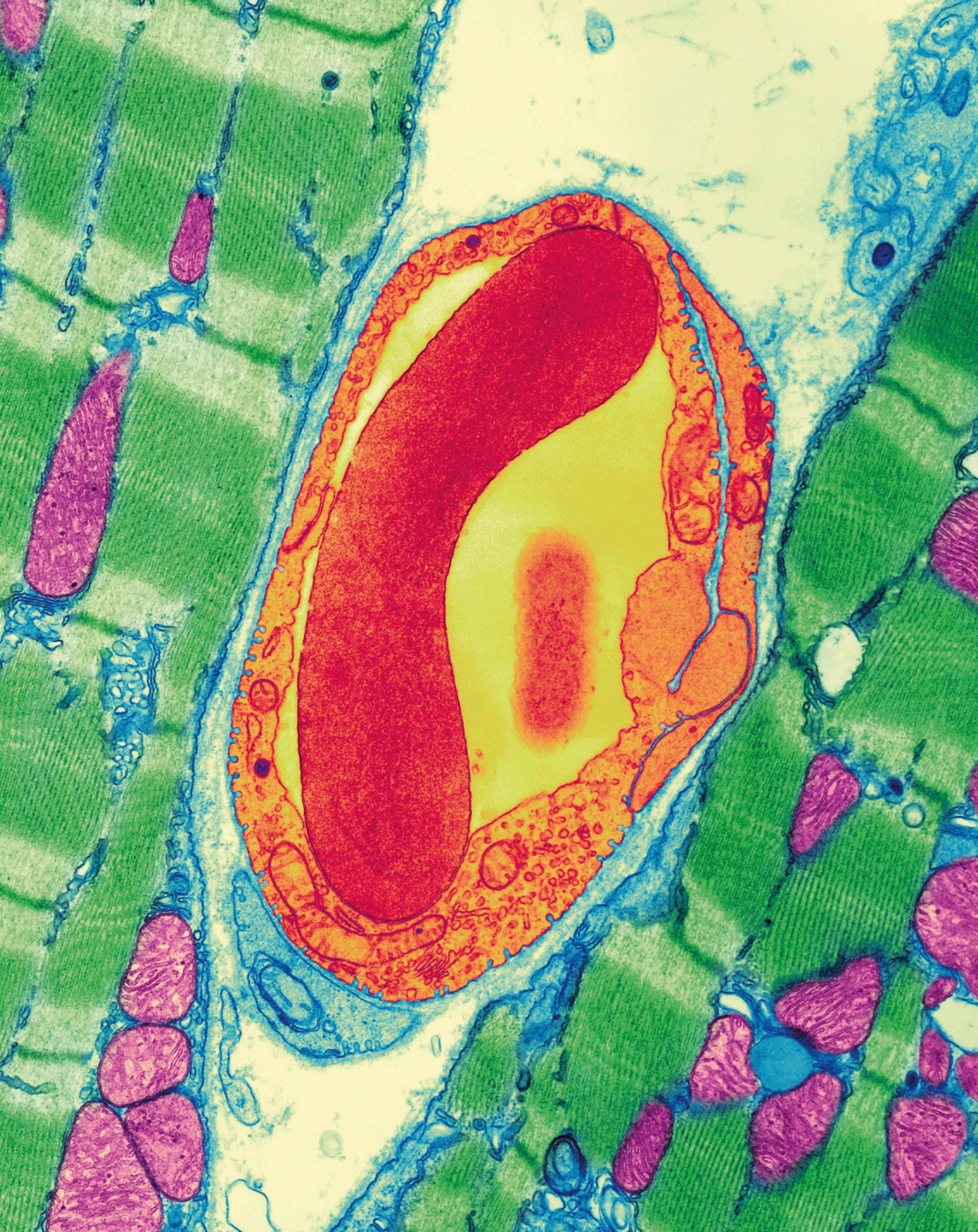
You will examine the relationship between these transport systems and compare the nutrient and gas requirements of organisms.

Outcomes

By the end of this module you will be able to:

- select and process appropriate qualitative and quantitative data and information using a range of appropriate media BIO11-4
- solve scientific problems using primary and secondary data, critical thinking skills and scientific processes BIO11-6
- communicate scientific understanding using suitable language and terminology for a specific audience or purpose BIO11-7
- explain the structure and function of multicellular organisms and describe how the coordinated activities of cells, tissues and organs contribute to macroscopic processes in organisms BIO11-9





CHAPTER 04

Organisation of cells

In this chapter, you will learn how cells are arranged in a multicellular organism to fulfil the needs of each cell and enable the whole organism to survive, grow and reproduce. You will compare unicellular, colonial and multicellular organisms and investigate the structures and functions of their specialised cells and organelles.

As multicellular organisms increase in complexity, so too does the organisation of their cells. The levels of organisation in complex multicellular organisms are: organelles, cells, tissues, organs and systems. You will look at each of these levels of organisation and the specialised structures and functions that have evolved to meet the needs of complex multicellular organisms.

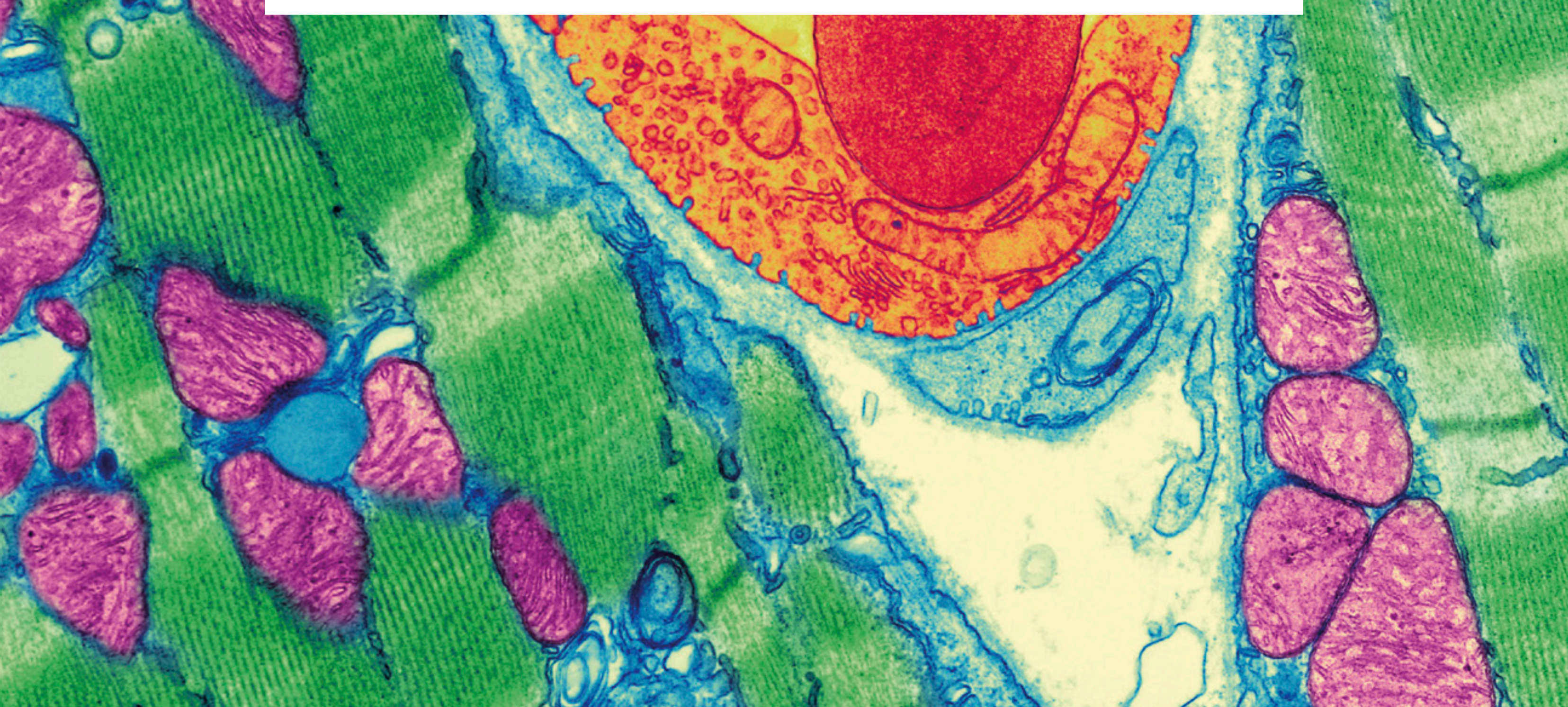
Content

INQUIRY QUESTION

How are cells arranged in a multicellular organism?

By the end of this chapter you will be able to:

- compare the differences between unicellular, colonial and multicellular organisms by:
  - investigating structures at the level of the cell and organelle
  - relating structure of cells and cell specialisation to function
- investigate the structure and function of tissues, organs and systems and relate those functions to cell differentiation and specialisation (ACSBL055) ICT
- justify the hierarchical structural organisation of organelles, cells, tissues, organs, systems and organisms (ACSBL054) CCT



4.1 Cellular arrangements of organisms

WS 2.1

Cells carry out all the functions necessary to sustain life, including obtaining nutrients and water, exchanging gases, sourcing energy, removing waste products and reproducing. In this section, you will explore the differences between unicellular, colonial and multicellular organisms, the origin of multicellularity, and the advantages and disadvantages of being multicellular.

UNICELLULAR ORGANISMS

FIGURE 4.1.1 The simplest form of organisation in organisms is a single cell. *Euglena* is a eukaryotic protist that carries out all the functions necessary for life in one cell.

GO TO ➤ Section 2.1 page 69

The first life forms on Earth were **unicellular** (single-celled) **organisms** that arose more than 3.8 billion years ago. In unicellular organisms, such as the prokaryote *Escherichia coli* and the eukaryote *Euglena* (Figure 4.1.1), a single **cell** must carry out all functions, including obtaining nutrients, exchanging gases, removing waste and reproducing. In **colonial** and **multicellular** (many-celled) organisms, these functions are shared between different individuals or different types of specialised cells. Unicellular organisms can live together in groups; however, each cell is still capable of breaking away and living individually. Unicellular organisms are examined in more detail in Chapter 2.

MULTICELLULAR ORGANISMS

A multicellular organism is like a community of cells that work cooperatively for the survival and **reproduction** of the organism. All multicellular organisms consist of eukaryotic cells. There is an enormous diversity of multicellular organisms, from simple mosses through to complex flowering plants, birds and mammals.

The earliest known multicellular animals are the Ediacaran animals (Figure 4.1.2). They are named after the Ediacara Hills in the Flinders Ranges of South Australia, where their fossils were first discovered. Ediacarans evolved more than 600 million years ago. Some resemble modern sea jellies or segmented worms. Others are unlike any other known organisms.

FIGURE 4.1.2 A representation of Ediacaran animals, the earliest known multicellular animals

For an organism to be considered truly multicellular, it must have multiple specialised cells that are responsible for specific functions (one of which must be reproduction). In addition, its cells must:

- have the same **DNA** (except for the reproductive cells)
- be connected and must communicate and cooperate to function as a single organism
- be dependent on each other for survival.

Colonial organisms

A colonial organism is a special form of multicellular organism that consists of many individuals living together. There are two types of colonial organisms: those that form a **facultative colony** and those that form an **obligate colony**. Facultative colonies are usually independent organisms that aggregate together to form complex social structures that increase the chance of survival, for example honey bees. Obligate colonies consist of individuals called **zooids** that vary in form and carry out specific functions for the organism to survive. Individuals in an obligate **colony** are dependent on one another for survival and reproduction and are sometimes physically connected. Examples of obligate colonial organisms are parasites, which need a host to complete part of a life cycle, or sea jellies, which are made up of individuals with specialised roles (e.g. digestion or reproduction).

Prokaryotes are not multicellular organisms. However, some bacteria, such as cyanobacteria, grow in chains of cells. Others form aggregates or colonies of cells that behave in a coordinated fashion, such as species that form biofilms.

Multicellularity is more energy efficient than unicellularity and allows more biological complexity.

The features of unicellular, colonial and multicellular organisms are listed in Table 4.1.1.

TABLE 4.1.1 Features of unicellular, colonial and multicellular organisms

Unicellular	Colonial	Multicellular
single cell	many cells	many cells
mostly prokaryotes (and some eukaryotes)	eukaryotes	eukaryotes
one cell carries out all the functions to sustain life	individual animals (e.g. zooids) work together to perform functions to sustain the colony	cells are specialised to perform specific functions required by the organism
functions are carried out within the cell	functions are carried out by individuals (zooids) with specific roles within the colony	functions are carried out at cellular, tissue, organ and system level (some simple multicellular organisms function only at the cell or tissue level)
microscopic size—surface area to volume ratio limits size	usually macroscopic	macroscopic size—increasing the number of cells allows increased body size
short lifespan due to energetically expensive workload for one cell	long lifespan, as work and energy costs are shared by cells within the colony	long lifespan, as work is efficiently divided between specialised cells
mostly asexual, clonal reproduction	mostly asexual, clonal reproduction; sexual reproduction is present in some species	mostly sexual reproduction
whole organism is involved in reproduction	usually specific zooids are responsible for reproduction	only cells specialised for reproduction will reproduce (gametes)

Colonies are made up of individual organisms that work together and depend on one another for survival and reproduction.

Multicellular organisms are made up of many specialised cells that carry out specialised roles for the survival and reproduction of the whole organism.

BIOFILE S

Dangerous colonies

The Portuguese man-of-war (*Physalia physalia*), also known as a blue bottle, is regularly encountered along Australia's coastline, particularly on exposed ocean beaches after storm events (Figure 4.1.3). This organism is commonly mistaken as a sea jelly. However, it is an obligate colony that consists of three distinct zooids: the tentacles, digestive polyps and reproductive polyps. The zooids cannot survive without one another, because they each perform specific functions. While the Portuguese man-of-war is generally found in warmer, tropical waters, it is becoming more common in temperate waters of Australia, including Victoria and Tasmania. Warming waters due to climate change and overfishing of predators are providing the Portuguese man-of-war with opportunities to expand its distribution southward.

FIGURE 4.1.3 The Portuguese man-of-war (*Physalia physalia*) is a colonial marine organism that can be found along beaches after strong winds or tides.

+ ADDITIONAL

Evolution of multicellular organisms

Multicellularity is thought to have evolved several times. However, the exact mechanism of its **evolution** is not fully understood, and it is possible that a different mechanism was involved each time. Scientists have proposed three possible mechanisms for the development of multicellularity:

- symbiotic theory
- syncytial theory
- colonial theory.

Symbiotic theory

The symbiotic theory suggests that multicellular organisms developed when different species of unicellular organisms began to cooperate (mutualism). Because this benefited each organism, over time the cells from the different species became dependent on each other for survival. They began to specialise and carry out different functions (Figure 4.1.4). Eventually, the DNA of the different species combined and a new multicellular organism evolved.

This type of mutually beneficial relationship, known as symbiosis, is common among living things. (You will learn more about symbiosis in Chapter 11.)

A major problem with this theory is that it does not explain how the DNA of the two species would have initially combined.

Syncytial theory

The syncytial theory, also called the cellularisation theory, suggests that a single cell with multiple nuclei evolved internal membranes that partitioned each nuclei. The partitions then began to specialise and eventually became separate cells, forming a multicellular organism (Figure 4.1.5).

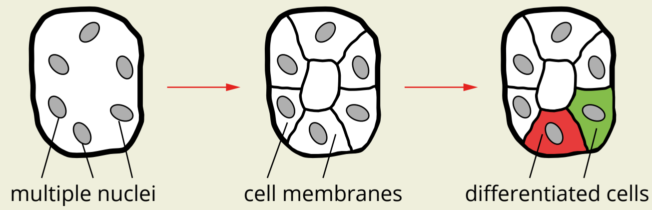


FIGURE 4.1.5 The syncytial theory proposes that multicellular organisms developed from a single-celled organism with multiple nuclei that formed internal membranes and began to specialise.

Evidence that supports this theory includes the many organisms that have multiple nuclei, such as ciliates and slime moulds. Ciliates are protists characterised by the presence of cilia. Ciliates have two nuclei: a smaller one for reproduction and a larger one for general cell functioning. Some slime moulds (which are also protists) spend part of their life cycle as a plasmodium (a mass of cytoplasm that contains many nuclei) (Figure 4.1.6).

FIGURE 4.1.6 The plasmodial stage of a slime mould. In this stage of the life cycle, the cells are a mass of cytoplasm with multiple nuclei.

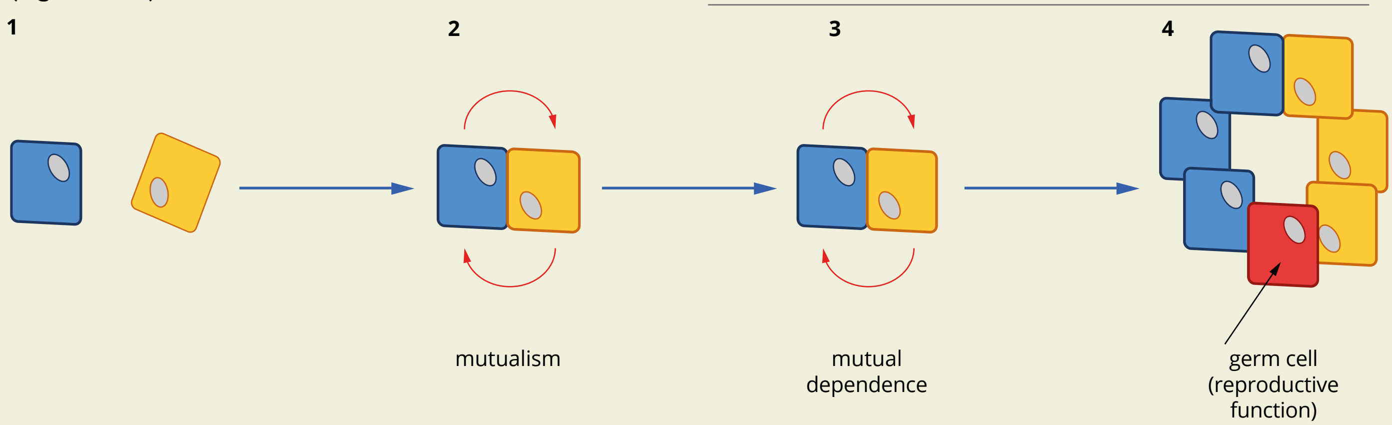


FIGURE 4.1.4 The symbiotic theory of the evolution of multicellular organisms proposes that two independent unicellular organisms (1) began to cooperate, gaining mutual benefit from their relationship (2). Eventually these two independent cells became dependent on one other for survival (3) and their cells adapted to carry out different functions (4).

Two arguments against this theory are that the multiple nuclei tend to have different roles, and that they are present in only one stage of the organism's life cycle.

Colonial theory

The colonial theory suggests that when a single cell divided, the new cells did not separate fully. This partial cell division continued, and the cells formed a colony and began to specialise and carry out different functions (Figure 4.1.7). Eventually, some formed reproductive cells. The new multicellular organism was then capable of replicating itself.

Colonial theory currently appears to be the most likely mechanism for the evolution of multicellular cells. Unlike the symbiotic theory, it explains why the DNA of cells in modern organisms is the same.

The formation of colonial organisms has also been observed on many occasions. One example is the unicellular amoeba *Dictyostelium*. When food is scarce, the individual cells group together and move in search of food. The colony moves in a coordinated fashion, and individual cells begin to develop some specialisations.

Another example of a colonial organism is *Volvox*. A typical *Volvox* colony consists of hundreds to thousands of cells. Each cell has two flagella and an eyespot. The colony, which is shaped like a hollow ball (Figure 4.1.8), swims in a coordinated way towards light. The cells at the front of the colony have more developed eyespots, while the cells at the rear of the colony have more developed flagella.

New *Volvox* colonies grow inside the sphere, and the parent *Volvox* colony turns itself inside out to release them. *Volvox* is more complex than some other colonial organisms, but it is not truly multicellular like fungi, plants and animals. The term **pluricellular** is often used to distinguish this type of colonial organism from true multicellular organisms.

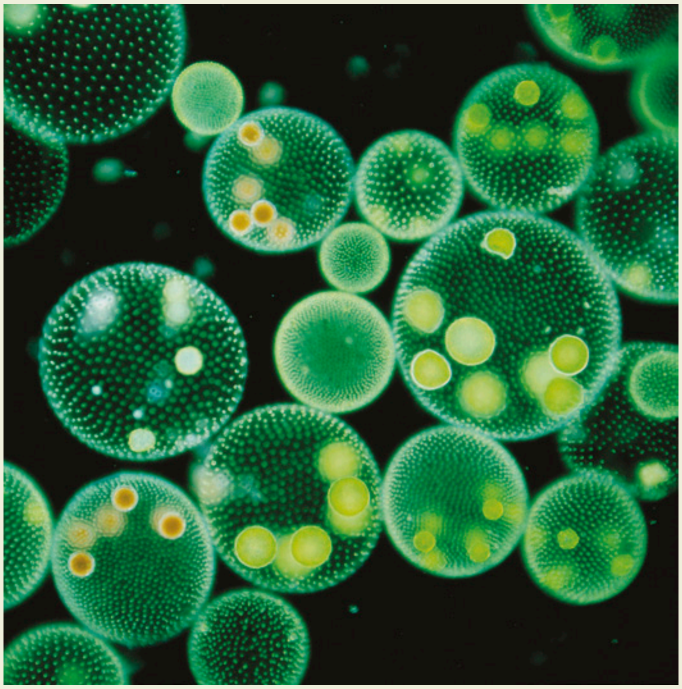


FIGURE 4.1.8 A light microscope image of *Volvox* colonies

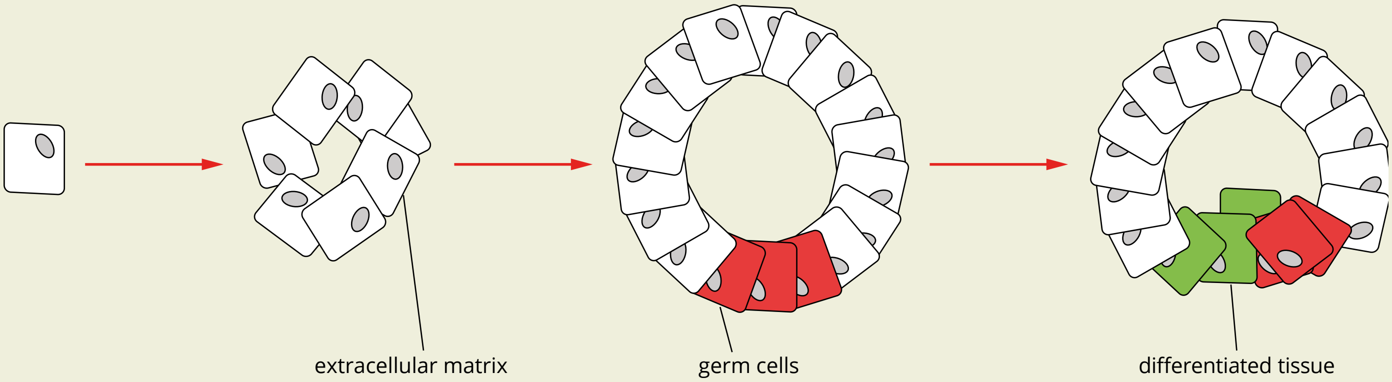


FIGURE 4.1.7 The colonial theory proposes that during cell division, cells did not divide properly and eventually formed a colony of specialised cells.

ADVANTAGES AND DISADVANTAGES OF MULTICELLULARITY

Almost all the life forms you can see around you are multicellular, eukaryotic organisms. The microscopic prokaryotes that surround you are invisible to the naked eye, yet they are incredibly abundant, diverse, survive in a remarkable range of environments and have been around for billions of years. Despite the success of prokaryotes, multicellular organisms continue to evolve and thrive, suggesting that being multicellular with specialised cells must have its advantages. Table 4.1.2 lists some advantages and disadvantages of multicellularity and **cell specialisation**.

The advantages of multicellularity outweigh the disadvantages. It is not surprising that evolution has favoured complex multicellular organisms that are organised into tissues, organs and organ systems.

TABLE 4.1.2 Advantages and disadvantages of multicellularity and cell specialisation

Advantages	Disadvantages
Multicellularity is energy efficient because specialised cells do not waste energy trying to complete all the functions necessary for life.	Having more cells means more energy is required for survival.
Multicellular organisms have longer lifespans than unicellular organisms because they are more energetically efficient.	The cells cannot function independently; they are dependent on the whole organism for survival.
Sexual reproduction and genetic recombination increases genetic diversity over generations compared with asexual, clonal reproduction in unicellular organisms. Genetic diversity allows populations to adapt to changing environments.	More energy is required for reproduction; most animals need to find a mate to reproduce, and most plants need to produce and disperse gametes.
Multicellular organisms are less vulnerable to short-term changes in their environment. They have more systems to cope with change, and cell death does not necessarily affect the survival of the organism.	Populations of multicellular organisms take much longer to evolve and adapt to long-term changes in their environment, because they have much longer generation times than unicellular organisms.
Multicellular organisms can grow significantly larger than unicellular organisms. Unicellular organisms must be small to obtain nutrients and remove waste efficiently by diffusion.	
Increased size and specialisation of limbs means multicellular organisms are more mobile and therefore more efficient at locating resources and avoiding predators and other negative stimuli.	
Multicellular organisms can perform more functions than unicellular organisms.	

4.1 Review

SUMMARY

- Unicellular organisms consist of a single cell that carries out all functions necessary for survival and reproduction.
- For an organism to be considered truly multicellular:
  - it must have multiple cells
  - its non-reproductive cells must have identical DNA
  - its cells must be connected and must communicate and cooperate to function as a single organism
  - it must have different cells that are specialised to carry out specific functions, one of which must be reproduction
  - its cells must be dependent on each other for survival.
- A colonial organism is a special form of multicellular organism that consists of many individuals living together.
- There are two types of colonies: facultative colonies and obligate colonies.
  - Facultative colonies are usually independent organisms that come together to form complex social structures to increase the chance of survival.
  - Obligate colonies consist of individuals called zooids that vary in form and carry out specific functions for the organism to survive.
- Multicellularity is thought to have evolved several times. The colonial theory is the most likely explanation for the evolution of multicellular organisms.
- Despite the success of prokaryotes, multicellular organisms continue to evolve and thrive, suggesting that being multicellular with specialised cells has advantages for survival, reproduction and evolution.
- Advantages of multicellularity are:
  - cell specialisation is energy efficient
  - longer lifespans
  - increased genetic diversity through sexual reproduction and genetic recombination
  - genetic diversity allows populations to adapt to changing environments
  - organisms are less vulnerable to short-term environmental changes
  - increased size and mobility helps organisms find ideal conditions and avoid predators and negative stimuli
  - organisms can perform more complex functions.
- Disadvantages of multicellularity are:
  - more energy is required for survival and reproduction
  - cells cannot function independently
  - it takes longer for populations to evolve and adapt.

KEY QUESTIONS

1 The tawny frogmouth and the eucalypt tree it is sitting in are both multicellular organisms. Describe why these organisms are considered multicellular using the following key terms: DNA, specialised, cooperate, organism, reproduction and survival.

2 List five differences between unicellular and multicellular organisms.

3 Why is a Portuguese man-of-war (*Physalia physalia*) classified as a colonial organism?

4 What are two disadvantages of multicellularity?

5 Explain the difference between a facultative colony and an obligate colony and give an example of each.

4.2 Levels of organisation in multicellular organisms

BIOLOGY INQUIRY CCT

Cell arrangement

How are cells arranged in a multicellular organism?

COLLECT THIS…

- bag of mixed lollies
- toothpicks (broken into two or three pieces)
- paper
- pen
- camera

DO THIS…

1. Think of a specialised structure (e.g. cell, tissue or organ) of an animal or plant. An example is the eye of an octopus.
2. Research how the structure functions and what features make it specialised.
3. Build the structure using mixed lollies, with different lollies representing different features. Use pieces of toothpick to hold the lollies together.
4. Ensure that all specialised features are present, for example the iris or retina of the eye.
5. Using small pieces of paper, label the important features of the structure and make note of any specialised organelles, cells or tissues.

RECORD THIS…

Describe how the specialised organelles, cells or tissues within your chosen structure help the structure function and help the organism survive.

Present photographs of your completed, labelled structure from various angles. Ensure there is a scale next to the model to indicate the actual size of the structure.

REFLECT ON THIS…

How are cells arranged in a multicellular organism?

Do all organisms have the same arrangement of organelles, cells or tissues?

How is this structure important for the survival or reproduction of the organism?

A multicellular organism can consist of many trillions of cells, which vary in size and function. Different types of cells have different **organelles** in different numbers. The number and types of organelles in a cell are related to the cell's function. For example, a muscle cell that uses a lot of energy will be packed with energy-producing mitochondria. Organelles carry out functions that are necessary for the cell's survival, while cells play important roles in the structure and function of **tissues**, **organs** and **systems**. All these components work together to promote the survival and reproduction of the whole organism. A mammal, such as a lion or human, has hundreds of different types of specialised cells (Figure 4.2.1), including muscle cells, red blood cells, bone cells and nerve cells.

While multicellularity has many advantages, it also has several disadvantages (Table 4.1.2, page 192). An individual muscle cell can shorten, yet on its own could not possibly bring about movement in a large organism. The same muscle cell requires nutrients and oxygen and produces waste. To ensure that cells can carry out their functions correctly and maintain healthy systems, the organism must expend energy finding the resources to fuel all its cells.

FIGURE 4.2.1 A complex multicellular organism, such as a lion, is more than just a mass of specialised cells. The cells are organised so that they can work together.

In this section, you will take a closer look at multicellular organisms and learn how they are organised to overcome these challenges and take full advantage of multicellularity.

LEVELS OF ORGANISATION

A cell must be able to obtain nutrients and remove waste, and physical conditions such as temperature, solute concentration and pH must remain within the tolerable limits of the cell. If any of these conditions are not met in a multicellular organism, cells could die.

One advantage of being a large, multicellular organism is that most body cells are isolated from the external environment by a protective outer layer called the **epidermis**. This outer layer provides a buffer against changes in the external environment, allowing conditions on the inside of the organism to be maintained at suitable levels for cells to function efficiently.

However, the isolation of the internal environment from the external environment means that most cells do not have direct access to their essential requirements, such as oxygen. It also means that wastes expelled from the cells need to be removed from the internal environment so that they do not accumulate. As an organism increases in size and complexity, its cells must be organised to allow greater cooperation and coordination. The term 'organism' is derived from the French word 'organisme', which means 'organise'.

Depending on their complexity, multicellular organisms can be organised into the following levels to meet the needs of the entire organism:

- organelles
- specialised cells
- tissues
- organs
- systems.

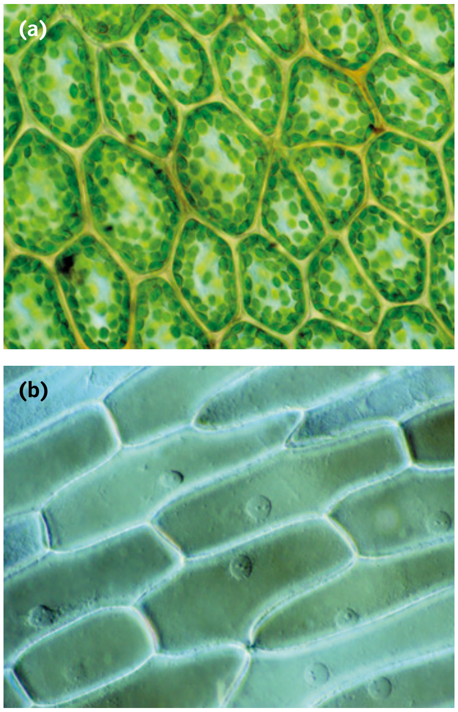


FIGURE 4.2.2 Cells have different organelles depending on the function of the cell. A plant's leaf cells (a) need large numbers of chloroplasts, the organelle that carries out photosynthesis. Cells of an onion (b), which grows underground, do not need chloroplasts, because photosynthesis is not required in these cells.

Organelles

Cells vary in the number and type of organelles they have, based on the cell's function (Figure 4.2.2). For example, animal cells that require large energy reserves will contain more mitochondria than other cells. Plant cells that require additional water to maintain their shape may possess larger vacuoles than other plant cells. And chloroplasts, the organelles that carry out photosynthesis, are only found in plant cells that photosynthesise, such as leaf cells. Organelles are covered in detail in Chapter 2.

GO TO ➤ Section 2.2 page 78

Specialised cells

Specialised cells are cells that have a specific function. All cells are adapted to perform different jobs in a multicellular organism, and have unique structural adaptations that enable them to carry out these functions. These specialised cells are the building blocks of complex tissues and organs in multicellular organisms. Examples of specialised cells in plants are root hair cells, which absorb and transport water; leaf palisade cells, which absorb light for photosynthesis; and leaf guard cells, which open and close to regulate gas exchange. In animals, specialised cells include myocytes (muscle cells), erythrocytes (red blood cells), epithelial cells and neurons. You will learn more about specialised cells in Section 4.3.

GO TO ➤ Section 4.3 page 208

Tissues

Specialised cells are organised into tissues. A tissue is a group of similar cells working together to carry out a specific function in a multicellular organism. For some organisms, this level of organisation is sufficient to meet all its needs. As organisms become more complex, tissues alone may not be enough to carry out all the tasks required. In these cases, tissues have evolved to group together in distinct structures called organs.

BIOFILE CCT N

Trillions of cells: the human body

Your body is made up of about 37 trillion cells. Most of these are red blood cells (26 trillion), but you also have about 1.8 billion bone cells, 3 billion pancreas cells, 6 billion heart cells, 10 billion kidney cells, 15 billion muscle cells, 17 billion brain cells, 50 billion fat cells, 360 billion liver cells and 100 billion nerve cells in your brain.

The most common cells in your body are not actually part of you. Your digestive tract alone contains about 100 trillion bacteria and other microorganisms (Figure 4.2.3). That's almost three times the number of cells that make up your body. Most of these bacteria are beneficial to digestion, but pathogenic species, such as *Salmonella enterica*, may sometimes enter the digestive system through contaminated food and cause illness.

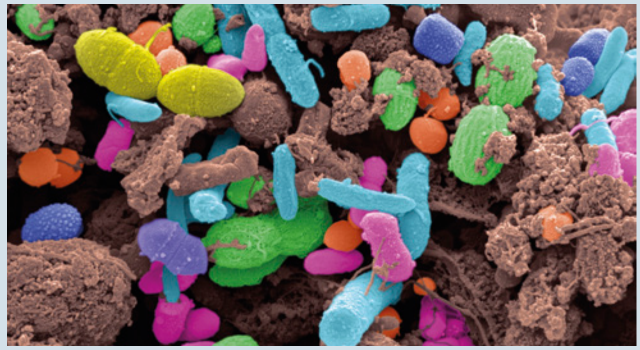


FIGURE 4.2.3 Most of the cells in your body are not your own. The human digestive tract contains approximately 100 trillion bacteria. This SEM image shows a sample of faecal matter with bacteria (coloured cells) that have been shed from the digestive tract.

Organs

An organ consists of two or more tissues that work together to perform one or more specialised tasks. An organ is commonly recognisable as a distinct structure. Examples of organs are flowers, leaves and roots in plants; and the heart, liver and brain in mammals.

Systems

In multicellular organisms, an organ rarely functions independently of other organs. Instead, organs form systems. A system is a group of organs that work together to perform a vital task, such as the circulatory and respiratory systems in humans.

As biological structures and functions become more complex, cells become more and more specialised.

Organisms

The final level of organisation is the organism itself. In a complex animal, systems work together and contribute to the successful functioning and reproduction of the whole organism (Figures 4.2.4 and 4.2.5).

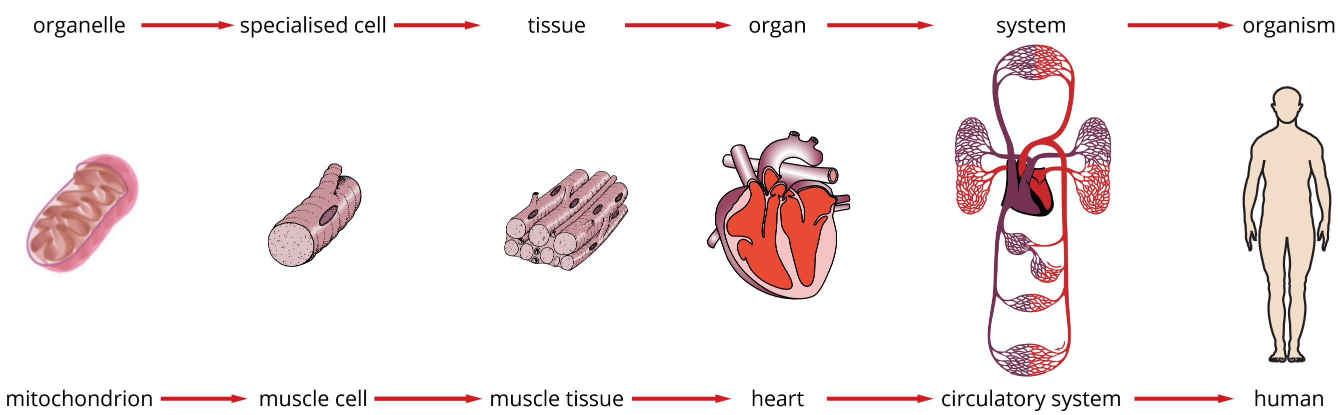


FIGURE 4.2.4 The levels of organisation in a complex multicellular animal

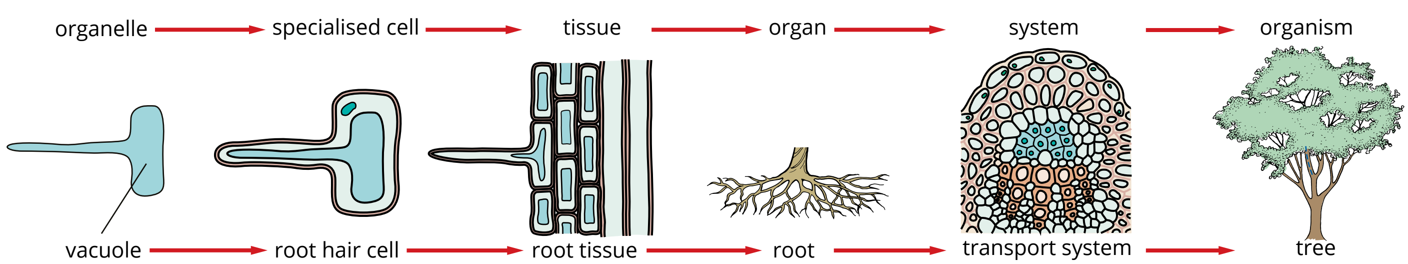


FIGURE 4.2.5 The levels of organisation in a complex multicellular plant

ORGANISATION IN SIMPLE MULTICELLULAR ORGANISMS

Some multicellular organisms are organised only at the cellular level. This includes simple multicellular organisms, such as sponges. These animals are considered tissue-less multicellular organisms, because their cells are not organised into discrete, functioning systems within the organism.

Although simple multicellular organisms are more complex than unicellular organisms, they can survive without organising their cells into true tissues and organs, because they are often only a few cells thick (Figure 4.2.6). This means that materials can easily diffuse into, out of and between cells. This lack of organisational complexity also means that many simple multicellular organisms, such as sponges, can regenerate. They can build new limbs or even an entirely new organism from just a tiny piece of their body or a single cell.

In sponges, the body is hollow and consists of two layers of eukaryotic cells separated by a jelly-like substance. The outer layer protects the sponge and contains tiny pores through which water and food can enter. Sponges are filter feeders, filtering plankton, bacteria, dinoflagellates and many other microscopic organisms from the water around them. Digestion is carried out within food vacuoles inside the cells of the sponge. The inner layer consists of several cell types, including collar cells and amoebocytes (Figure 4.2.6 and Table 4.2.1).

The simplest multicellular organisms do not have tissues, organs or systems.

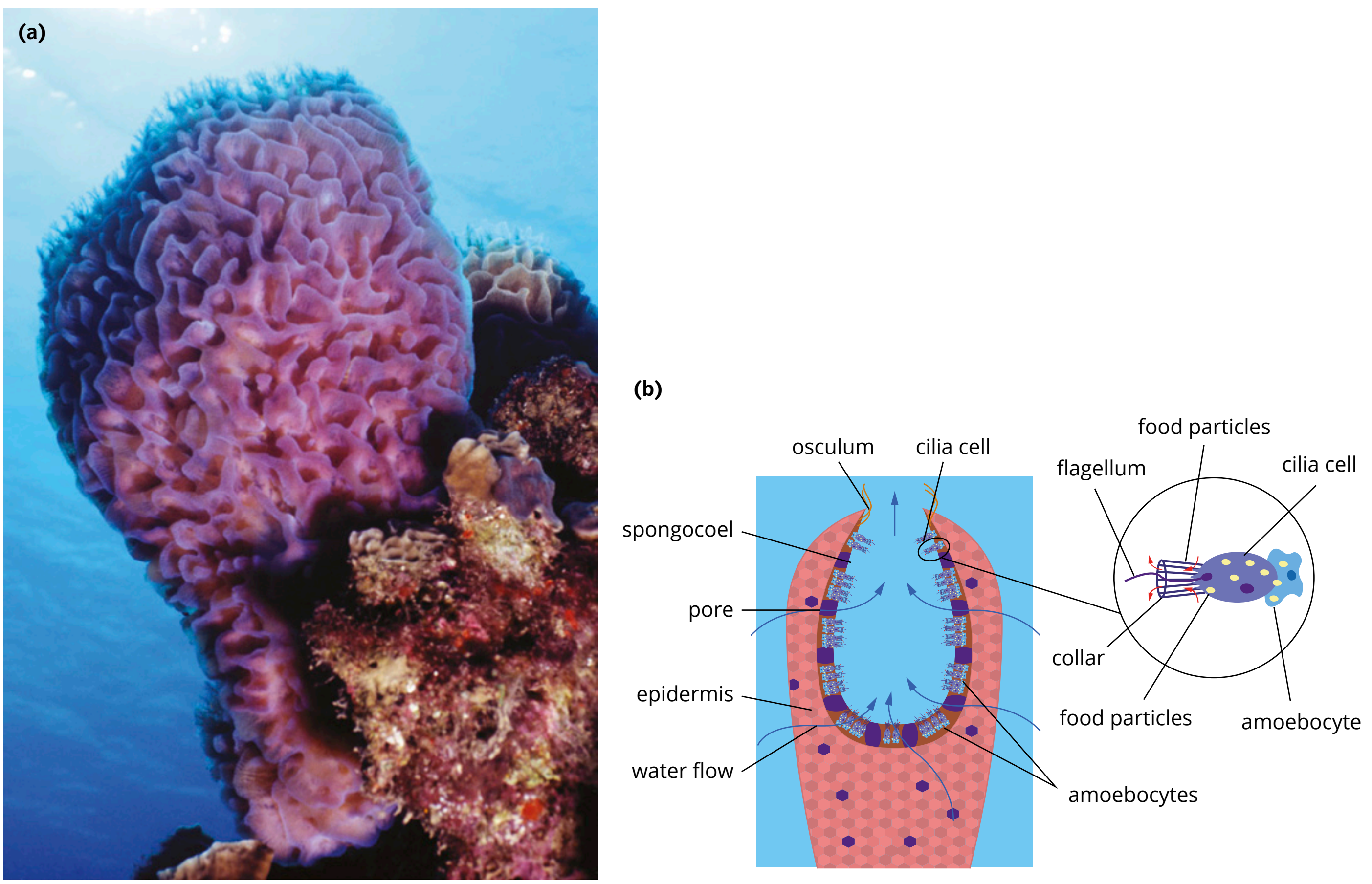


FIGURE 4.2.6 Sponges, such as the azure vase sponge (*Callyspongia plicifera*) (a), are organised at the cellular level, with different types of cells performing different functions (b). Although the cells work together, they do not form true tissues or organs. Sponges are often referred to as tissue-less multicellular organisms.

Sponges have some unique methods of defence against predators and disease-causing organisms. They produce toxins that prevent predators from eating them, and powerful antibiotics that fight infections from bacteria. Scientists are studying these chemicals as possible new medicines for human use. Cnidarians (sea jellies and anemones) have specialised cells for defence and capturing prey. These cells are called cnidocytes or nematocytes, and are found along the tentacles of cnidarians (Figure 4.2.7). A thread is fired from the cnidocyte, which wraps around and traps prey. Some species, such as sea jellies or anemones, have cnidocytes that contain toxins for stinging and paralysing prey.

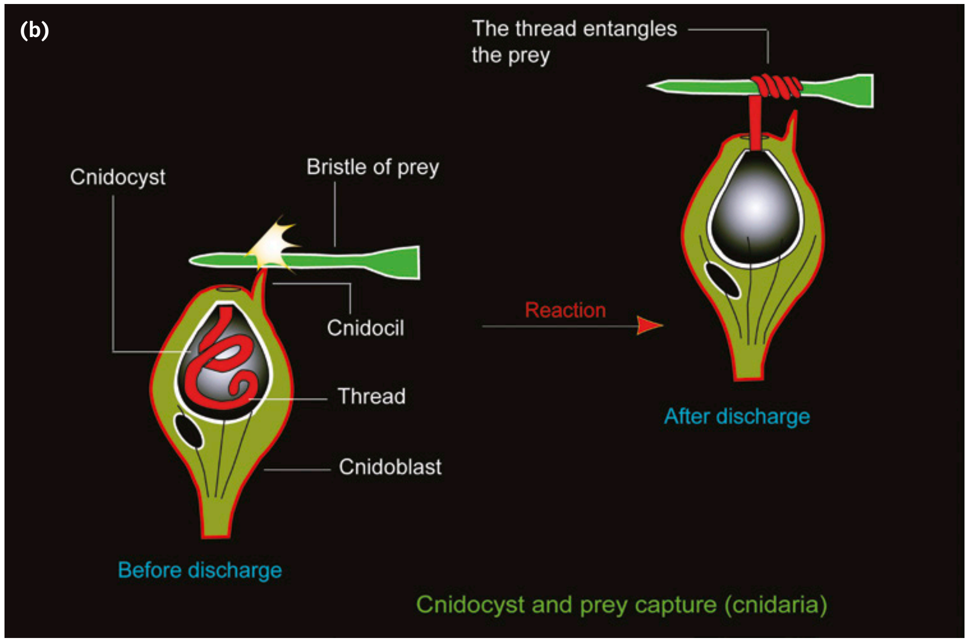


FIGURE 4.2.7 Simple multicellular organisms often have complex, specialised cells. This cnidarian (*Ectopleura larynx*) (a) is a marine animal with cells called cnidocytes or nematocytes along its tentacles. (b) A thread is fired from the cnidocyst—a capsule within the cnidocyte—wrapping around and trapping prey.

Despite the simple organisation of these organisms, each of the different cell types found within them has a specialised function that contributes to their survival and reproduction (Table 4.2.1).

TABLE 4.2.1 Structure and function of specialised cell types in sponges

Cell type	Function	Structure
epidermal cells	• protect the inner layer of cells	• thin, leathery • closely packed together
collar cells	• move water through the sponge's pores and into the central cavity (spongocoel) using the motion of their flagella • absorb nutrients	• flagella • hollow 'collar'
amoebocytes	• ingest and digest food caught by the collar cells • transport nutrients to the other cells of the sponge	• mobile and flexible

ORGANISATION IN COMPLEX PLANTS

Complex plants are those that have specialised tissues for transporting water and nutrients. These plants are called vascular plants, and the specialised tissues are known as **vascular tissues**. Non-vascular plants, such as algae and mosses, do not have vascular tissue or true organs. Instead, they have simplified tissues and absorb water directly through their cell walls, transporting it between cells via osmosis.

The absence of vascular tissue in non-vascular plants also limits their size, due to the lack of structural support and limited area over which they can transport water and nutrients.

In comparison, a cellular level of organisation cannot meet the needs of larger and more complex organisms, such as vascular plants. Consequently, cells in complex plants such as angiosperms (flowering plants) and conifers are organised into higher levels of organisation: tissues, organs and systems.

Specialised cells in complex plants

Some of the most important functions in vascular plants are involved in the transport of nutrients and water and acquiring energy via photosynthesis. Many specialised cells are found within the vascular tissue of plants for these functions.

Tissues in complex plants

The characteristic tissues in vascular plants (and the basis of this type of plant's name) are the vascular tissues, which are involved in the transport of water and nutrients throughout the plant. There are two types of vascular tissue: xylem and phloem. You will learn more about the tissues of plants in Chapters 5 and 6.

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Organs in complex plants

The major organs of vascular plants are roots, leaves, stems, flowers and fruits.

Roots

Roots are responsible for absorbing and storing water and nutrients (mineral ions) from the soil. Roots also support and anchor the plant to the ground. Root systems are often very complex and can be much larger than the above-ground structures of the plant. The large root systems of many trees in nutrient-poor rainforest soils do not penetrate deep into the soil layers and instead grow above ground (Figure 4.2.8).

FIGURE 4.2.8 Two major organs of vascular plants are the leaves and roots, both of which are visible in this Amazonian tree with exposed buttress roots.

Leaves

Leaves are the primary organ of photosynthesis. Photosynthesis is carried out to convert light energy into chemical energy, which fuels the organism's cells. A flat shape and large surface area makes leaves well-suited to absorbing sunlight for photosynthesis. The major tissues that make up a leaf are the epidermis, photosynthetic tissue and vascular tissue. The vascular tissue (xylem and phloem) is visible as veins in the leaf structure (Figure 4.2.9).

Stems

The primary functions of stems are to:

- support the plant's leaves, flowers and fruit
- store nutrients
- transport water and nutrients between the roots and the shoots
- grow new plant tissue.

The stem is made up of three tissue types: dermal tissue, ground tissue and vascular tissue. The structure of stems varies widely between different species. For example, the stems of strawberry runners are flexible and fleshy, while the stem or trunk of an oak tree is thick and woody. Some stems are even edible, such as asparagus and celery stalks.

Flowers

Flowers are the reproductive structures of angiosperms. Flowers facilitate the fertilisation of the ovules (contained within the ovary) by the sperm (contained within pollen). The structures of many flowers are highly specialised to attract pollinators, such as bees, moths and fruit bats, which disperse the pollen from one flower to another. Other flowers produce pollen that is specialised for wind dispersal. Following fertilisation, the seeds develop and the surrounding ovary grows into a fruit.

FIGURE 4.2.9 Many of the major organs of vascular plants can be seen on this orange tree, including leaves, stems, flowers and fruits.

Fruits

Fruits protect developing seeds and help them disperse from the parent plant. Fruits develop from the mature ovaries of flowers and often have a fleshy outer layer that surrounds the seeds. The outer structure of the fruit is often specialised to attract animals that aid in seed dispersal. Some animals, such as birds, eat the fruit and later excrete the seeds, while others disperse seeds that have attached to their fur. Examples of fruits are nuts, legumes, berries, peaches, tomatoes and oranges (Figure 4.2.9).

Systems in complex plants

Vascular plants have two systems: the root system and the shoot system. The root system, which is usually underground, supports the structure of the plant and absorbs water and nutrients from the soil. The shoot system is made up of two parts: the non-reproductive (vegetative) parts of the plant, such as leaves and stems, and the reproductive parts, such as flowers and fruits.

ORGANISATION IN COMPLEX ANIMALS

The animal kingdom includes the most complex types of multicellular organisms. A cellular level of organisation is not enough to meet the needs of complex animals, so their specialised cells are organised into tissues, organs and systems.

Specialised cells in complex animals

Most complex animals are made up of hundreds of different cell types that are specialised to perform different functions. The roles of these cells are critical to the healthy functioning of the tissues, organs and systems of animals. Nerve cells or neurons (Figure 4.2.10) are an example of specialised cells in complex animals. These cells play essential roles in processing and transmitting signals throughout the body.

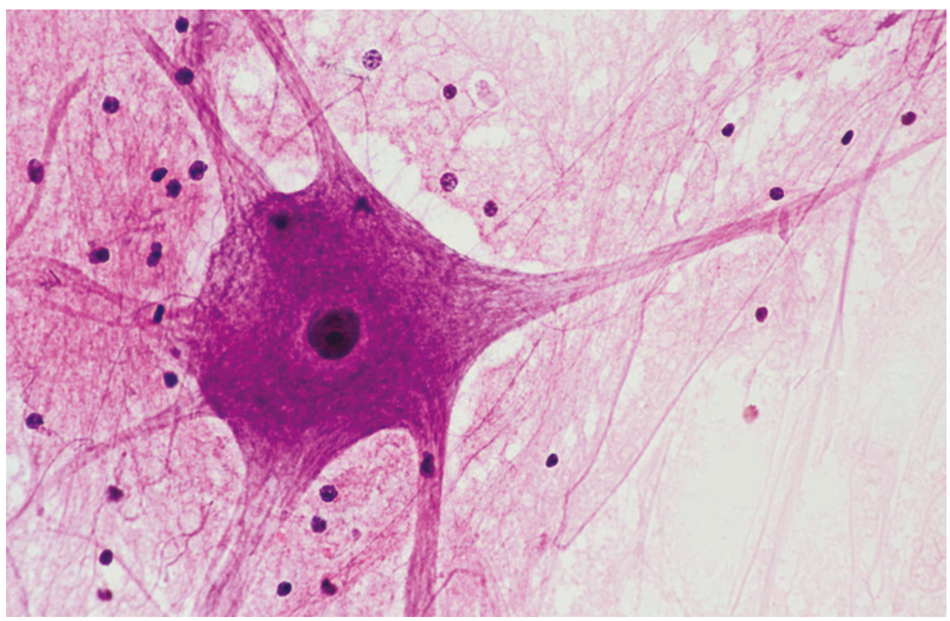


FIGURE 4.2.10 Motor neuron cell and surrounding neuroglial cells from the spinal cord. These specialised cells are part of the tissue of the nervous system, which is responsible for communicating signals that regulate and control bodily functions and activity in animals.

Tissues in complex animals

As described earlier, tissues contain specialised cells working together to complete a specific function. For example, a human red blood cell is perfectly adapted to absorbing and releasing oxygen as it travels around the body. However, one red blood cell cannot possibly carry all the oxygen that a human body needs. Trillions of red blood cells need to work together to meet the needs of a human.

Cells do not need to be identical to be considered a tissue; they just need to be working together to carry out a certain function. Blood, for example, is a tissue that consists of red blood cells, white blood cells and platelets all working together.

Tissues in complex animals are grouped into four main types (Figure 4.2.11):

- muscle tissue, formed by cells that can contract (e.g. skeletal and cardiac tissue)
- nerve tissue, consisting of highly specialised cells called neurons, which sense stimuli and transmit signals (Figure 4.2.10); this is essential for communication and coordination in complex multicellular animals
- connective tissue, forming the supporting and connecting structures of the body (e.g. bone and blood)
- epithelial tissue, formed by one or more layers of cells that cover most internal and external surfaces of the organism (e.g. skin and intestinal lining).

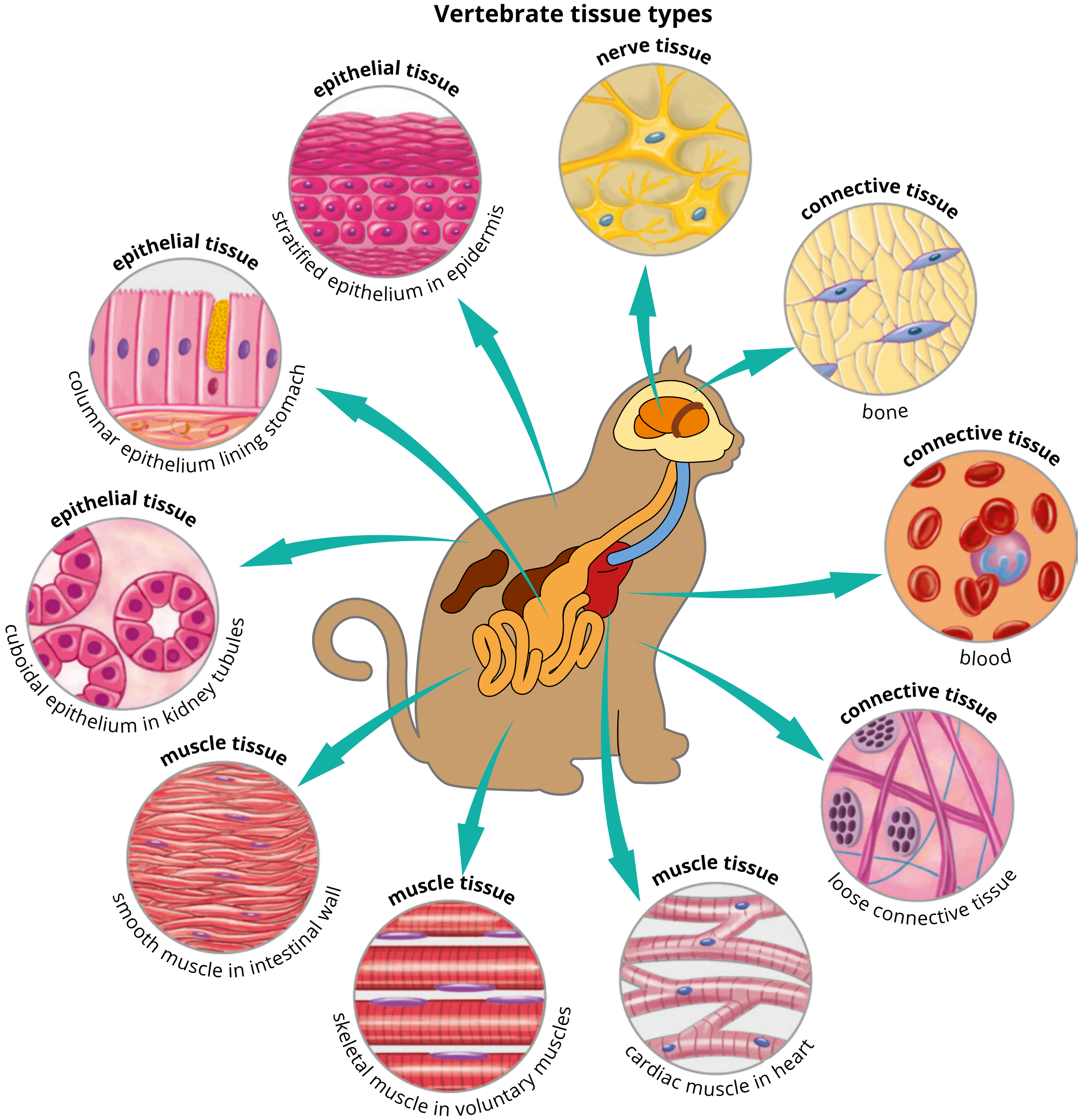


FIGURE 4.2.11 Complex multicellular organisms are made up of a diverse array of tissue types, which are specialised for many different functions.

Organs in complex animals

FIGURE 4.2.12 The head of a median wasp (*Dolichovespula media*), showing the external structure of the compound eyes

An organ is a structure made up of two or more tissues that perform a specific function that cannot be carried out at a tissue level. Some of the many organs in complex animals include the eye, skin and heart. The largest internal organ in the human body is the liver, but the largest organ overall is the skin. The smallest organ in the human body—the pineal gland—is located within the brain.

The eye

The function of the eye is vision. Insects have compound eyes that consist of thousands of individual units called ommatidia (Figures 4.2.12 and 4.2.13). Each ommatidium is like a single eye. Collectively, they are oriented to receive light from different directions, giving an insect a very wide angle of view. Each ommatidium consists of a lens, crystalline cone, light-sensitive visual cells and pigment cells (Figure 4.2.13). The pigment cells ensure that light hits the visual cells at the correct angle. The visual cells transfer a message to the optic nerve, which transmits information to the brain.

Insect vision is quite different from that of humans. The image generated is more like a light and dark mosaic, rather than a sharp picture. Insect eyes can also detect very fast movement from a wide range of directions, allowing them to react very quickly when something moves towards them.

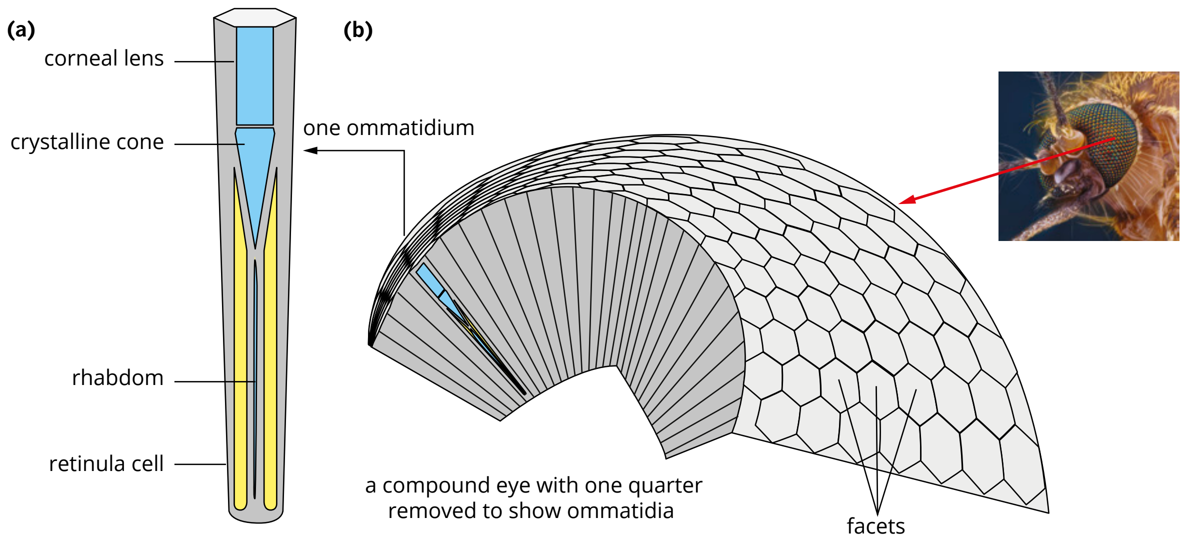


FIGURE 4.2.13 The compound eye of a mosquito. (a) The internal structure of an ommatidium. (b) The compound eyes of insects are made up of many ommatidia.

The skin

The skin is the largest organ of the human body. In an average adult, the skin is more than 1.8 m^2 and makes up 6–10% of the body's total weight. Skin is considered an organ because it carries out several functions, including regulating temperature, preventing water loss and sensing the environment. It also provides a protective barrier and contributes to a stable internal environment for the other cells, tissues, organs and systems that make up a human.

Skin in humans is divided into three layers: epidermis, dermis and subcutis (the subcutaneous fatty layer) (Figure 4.2.14).

The epidermis is the outermost layer and consists mostly of keratinocytes. Keratinocytes are cells that contain keratin and create a tough, waterproof layer for the body. The outer layer of the epidermis consists of dead cells, which are continually replaced by dividing cells below. The thickness of this layer of dead cells varies enormously over the body, and is 10 times thicker on the soles of the feet than on the face.

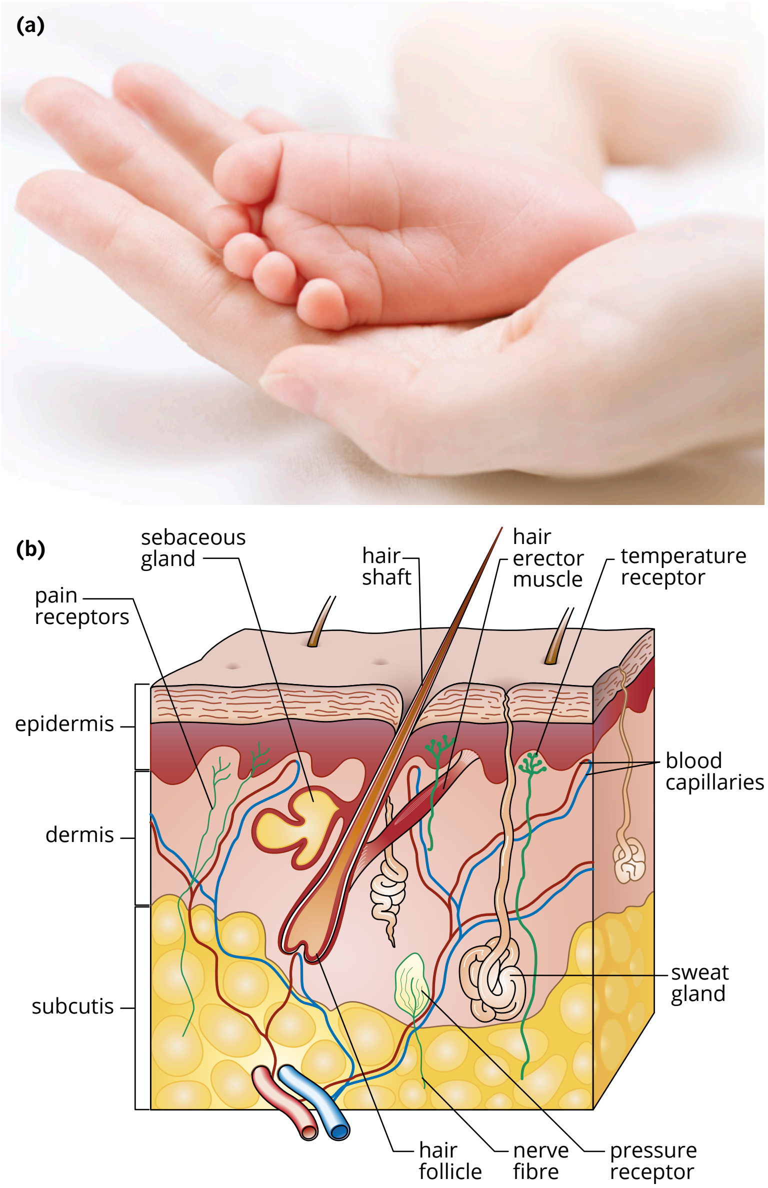


FIGURE 4.2.14 Human skin (a) is a complex organ consisting of many different types of specialised cells and tissues (b).

The dermis has a rich supply of blood vessels that control blood flow through the skin, regulating the body temperature of the whole organism. Fibres of collagen and elastin in the dermis give the skin strength and elasticity. The dermis also contains nerves and receptors that sense external stimuli, such as temperature, pressure and touch. Some touch receptors are attached to hair cells, while pain receptors are close to the surface of the skin in the dermis or epidermis. Sweat glands aid in cooling by releasing a watery substance (sweat) onto the epidermis via pores. Sebum is released by the sebaceous glands to help keep the skin and hair cells pliable. Sebum is also thought to have a mildly antiseptic effect on bacteria, because some of its fatty acid molecules inhibit bacterial growth.

The final layer of human skin, the subcutis, consists mainly of fat cells. These act as a food reserve for the body, provide insulation and cushion physical impact.

The heart

The heart of a complex animal beats continuously throughout the life of the organism, transporting nutrients and oxygen to cells and helping remove carbon dioxide and other waste products of cells. In a single year, the human heart beats more than 30 million times.

The human heart has two separate pumps (Figure 4.2.15). The right-hand pump receives blood from the body and pumps it to the lungs. The left-hand pump receives blood from the lungs and pumps it to the body.

Blood moves from the right ventricle to the lungs. In the lungs, oxygen binds to the haemoglobin in the red blood cells, while carbon dioxide diffuses into the lungs and is exhaled. Oxygen-rich blood then returns to the heart via the left atrium and moves to the left ventricle, which pumps the blood under high pressure to the body via the aorta. Blood eventually returns to the heart via the right atrium, completing the circuit.

The heart has several tissues. Most of the heart is composed of cardiac muscle tissue, which contracts to force blood through the heart and out to the body. Connective tissue makes up valves, which ensure blood moves through the heart in the right direction. Nerve tissue controls the heart rate. The most important nerve tissue is the sinoatrial node, located in the right atrium. This node generates the electrical impulses that sweep across the heart, causing it to contract and pump blood. It is often referred to as the natural pacemaker.

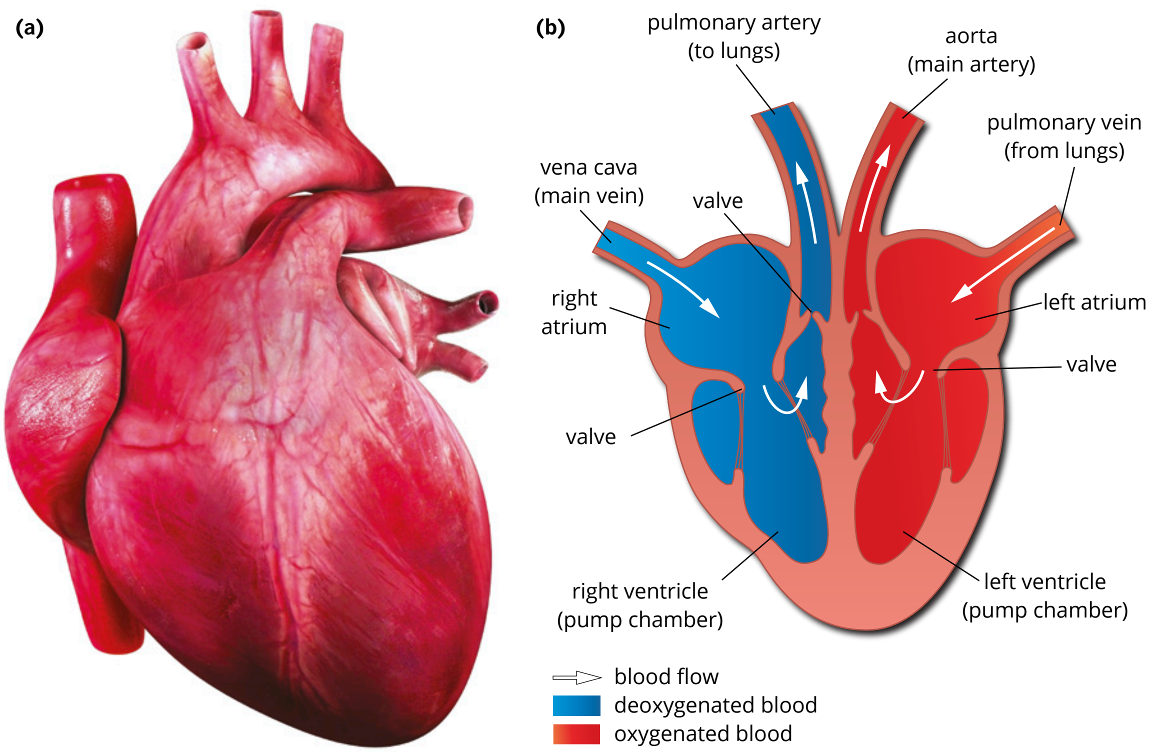


FIGURE 4.2.15 The human heart from (a) anatomical and (b) diagrammatic perspectives. The diagram shows the direction of blood flow into the heart through the veins, to the atria and ventricles. Blood then flows out of the heart, either to the lungs via the pulmonary artery, or to the rest of the body via the aorta.

BIOFILE CCT

Deep dives

The emperor penguin (*Aptenodytes forsteri*) is one of six penguin species that inhabits the Southern Ocean around Antarctica and is one of four species that breed on the mainland of Antarctica (Figure 4.2.16). They regularly dive 200–400 m deep in search of food, which requires them to hold their breath for three to six minutes. Some individuals have been recorded diving for as long as 22 minutes. To ensure adequate oxygen supply to cells during these dives, penguins have an arterial–venous shunt that directs arterial blood directly to the veins, avoiding the tissue. This reduces blood flow to the extremities and ensures adequate blood flow to the essential organs, such as the brain, during long, deep dives.

FIGURE 4.2.16 Emperor penguins (*Aptenodytes forsteri*) regularly dive to great depths for long periods in search of food.

BIOLOGY IN ACTION EU ICT

Organs on chips could end animal testing

The development of micro-devices that simulate organ-level functions could revolutionise the research and development of medicines—and potentially end the need for animal testing. Organs on chips are being developed by researchers at Harvard University to mimic the mechanical and chemical functions of organs on a micro-scale. The technology will enable much faster, cheaper and accurate research and testing of the safety and effectiveness of medicines, cosmetics, cleaning products and environmental pollutants, while reducing the need for the ethically unsound use of animals in the laboratory.

The memory stick-sized chips are made from a clear, flexible, polymer membrane lined with living human cells. The membrane sits at the centre of the chip, surrounded by fluid and air-conducting micro-channels. Because the chips are transparent, scientists can observe the internal physiological processes of the organs in real time (Figure 4.2.17). The organs on chips give scientists new insight into the functioning of cells, tissues and organs. Chips containing lung, kidney, liver, heart, skin, bone marrow and peristaltic gut cells have already been completed.

The lung on a chip consists of a porous membrane coated with human capillary cells on one side and human lung cells on the other side. Air flows through a channel on the lung cell side, while blood-like fluid containing red and white blood cells flows on the capillary side. A vacuum simulates the motion of breathing, stretching and relaxing the cells on the chip as if they were in a lung in a living organism (Figure 4.2.18). Using the lung on a chip, researchers have mimicked the effects of a lung infection. After introducing bacteria to the air channel, scientists observed white blood cells crossing the membrane to engulf bacteria that were attaching to the lung cells.

Once enough micro-organs have been developed, scientists can connect them to simulate a whole human system. This research paves the way for truly personalised medicine, by using your cells and DNA to test the compatibility and effectiveness of medications.

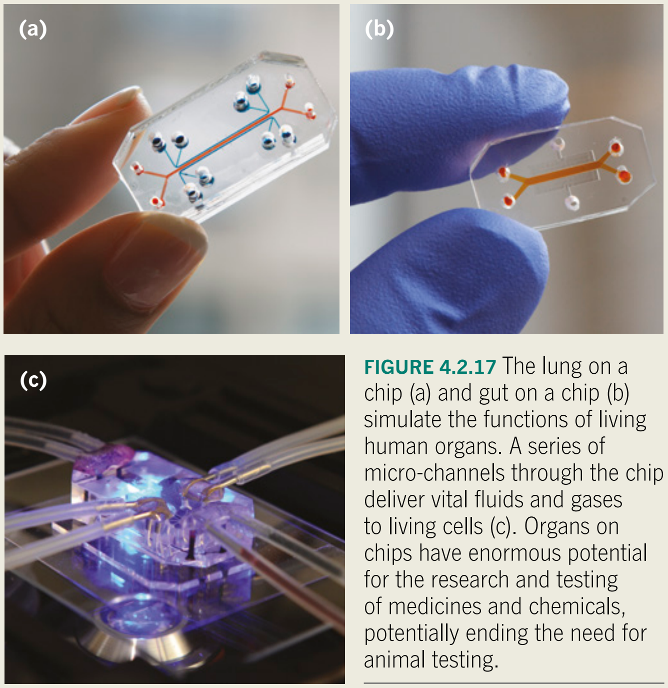


FIGURE 4.2.17 The lung on a chip (a) and gut on a chip (b) simulate the functions of living human organs. A series of micro-channels through the chip deliver vital fluids and gases to living cells (c). Organs on chips have enormous potential for the research and testing of medicines and chemicals, potentially ending the need for animal testing.

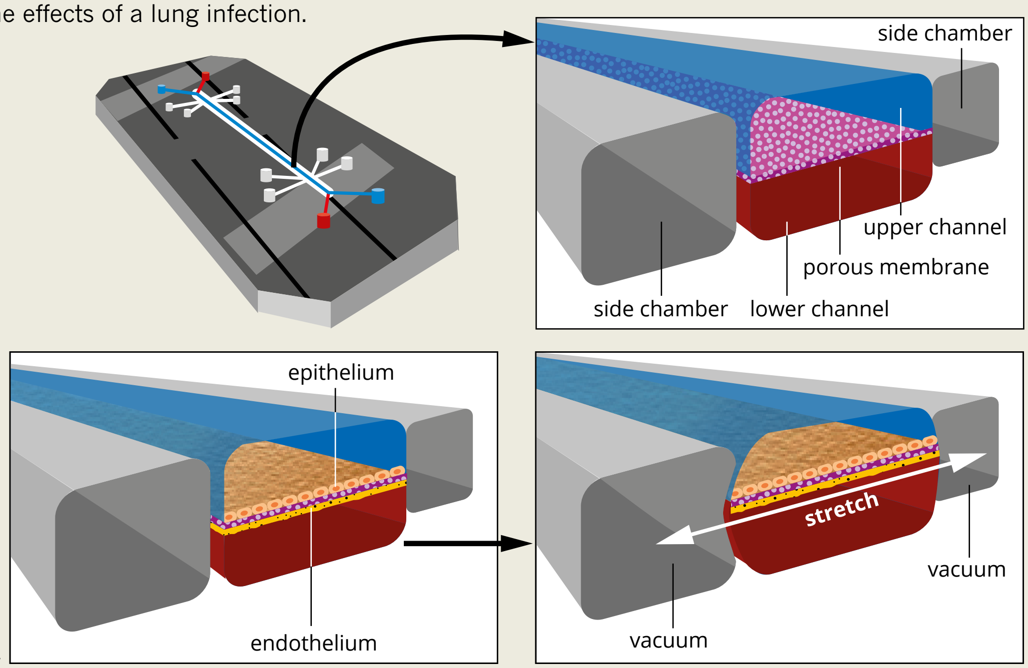


FIGURE 4.2.18 Internal view of a lung on a chip lined with living human lung cells (epithelium) and capillary cells (endothelium). Air flows through the upper channel across the lung cells, while the lower chamber conducts blood-like fluid. The side chambers function as vacuums to mimic the stretching and relaxing motion of breathing lungs.

Systems in complex animals

The organisation of cells into tissues may be enough to fulfil the biological requirements of simple animals, but more complex animals require further organisation of their organs. Systems are groups of functionally similar organs working together as a unit.

The major systems in complex animals are:

- respiratory
- circulatory
- digestive
- excretory
- immune
- nervous
- endocrine (glands and hormone secretion)
- reproductive
- muscular
- skeletal
- integumentary (skin, hair, nails and sweat glands).

WS 2.2

The grouping of organs into systems is the highest level of biological complexity. Mammals have 11 organ systems, each with specialised roles that are essential for the correct functioning of the organism (Figure 4.2.19). The systems do not work in isolation; they have vital connections to one another, and many of their functions overlap. Each of the systems ultimately functions to maintain homeostasis (internal stability) and ensure the survival and reproduction of the organism.

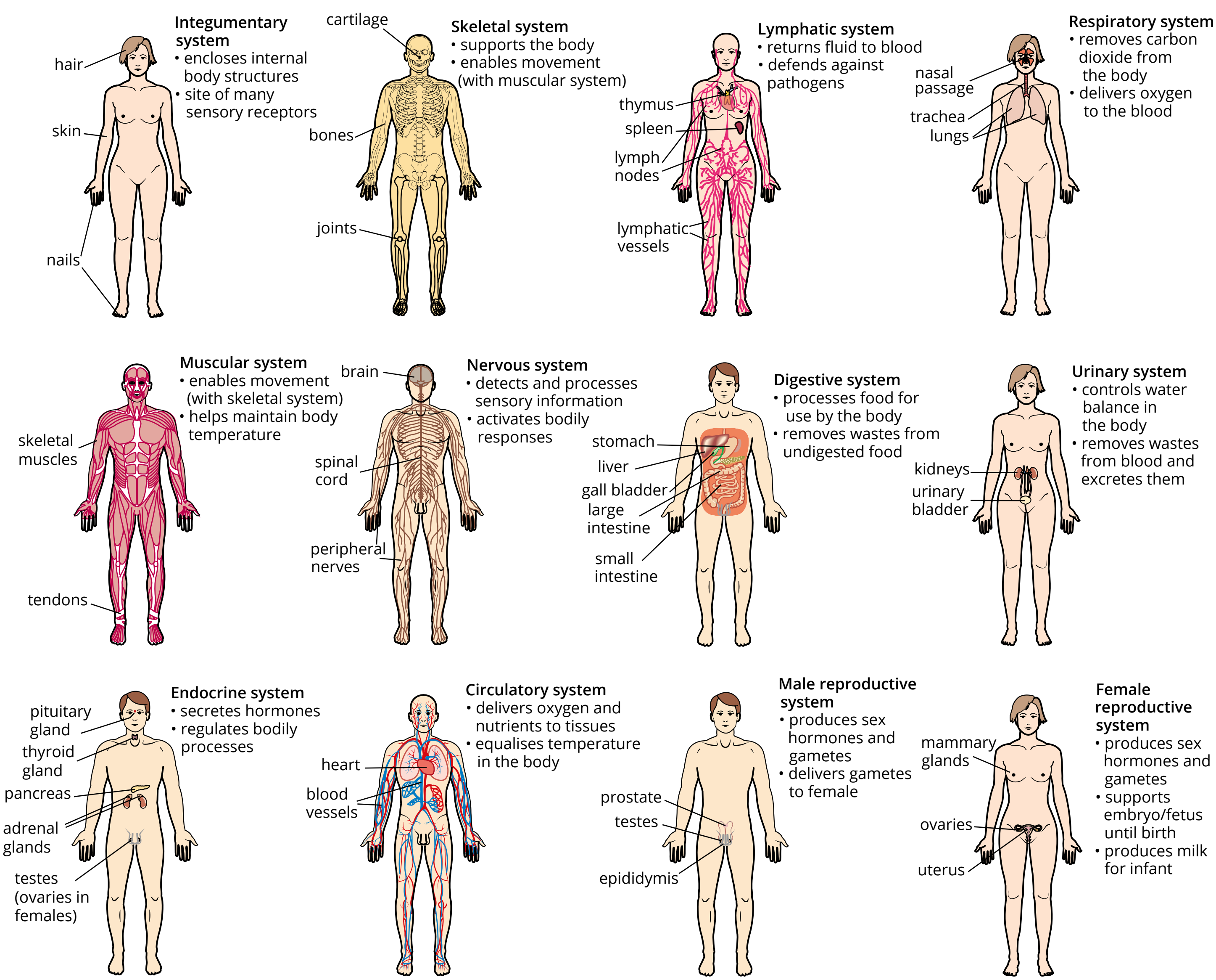


FIGURE 4.2.19 Systems of the human body

4.2 Review

SUMMARY

- In multicellular organisms, greater cooperation and coordination is required between cells because:
  - not all cells have direct access to the external environment, so they need some means of receiving nutrients and removing their accumulated wastes
  - specialised cells fulfil their own needs, but on their own cannot maintain a whole multicellular organism.
- Specialised cells perform a specific function, which is reflected in their structure.
- Tissues are groups of specialised cells working together to carry out a certain function.
- An organ consists of two or more tissues that work together to perform a specialised task. It is often recognisable as a distinct structure.
- A system is a group of organs that work together to perform a vital task.
- The highest level of organisation is the organism itself.

KEY QUESTIONS

1 Put the following levels of organisation in the correct order, from simplest to most complex: organ, specialised cell, organelle, system, organism, tissue.

2 Why is it important for multicellular organisms to be organised into cell groups, tissues, organs and systems?

3 What important role does the epidermis play in multicellular organisms?

4 Give four examples of organs in vascular plants and describe their functions.

5 Define tissue (as used in biology), and give examples of tissues found in vascular plants and animals.

6 Explain why blood is considered a tissue rather than specialised cells.

7 Why are animals such as sponges considered tissue-less multicellular organisms?

4.3 Cell differentiation and specialisation

While most cells within a multicellular organism will contain the same genetic material, they differentiate and specialise to perform different functions in different locations around the organism. This allows the organism to function more efficiently and increase its chance of survival and reproduction. In this section, you will learn more about the role of cell specialisation in multicellular organisms.

CELL SPECIALISATION

FIGURE 4.3.1 A zygote undergoing the first mitotic divisions leading to the development of a multicellular embryo

All multicellular organisms begin life as a single cell that resulted from the fusion of two highly specialised cells called **gametes**. These gametes are called the egg (or **ovum**) and **sperm**. Gametes are unique in being able to fuse together to form a single cell, called a **zygote**. This one cell contains all the genetic information required to develop into a fully functional multicellular organism. The zygote develops by cell division into an **embryo** (Figure 4.3.1). It is through **cell replication** and **cell differentiation** that one single cell can become the trillions of highly specialised cells that make up an organism.

Cell differentiation

Cell differentiation is the process by which unspecialised cells, called **stem cells**, become specialised cells. It takes place in all multicellular organisms. Stem cells are present in the embryo and some adult tissues of animals, and in **meristem** tissue in plants. Stem cells retain the ability to divide, while specialised cells cannot usually divide.

The process of cell differentiation begins shortly after **fertilisation**. Five days after fertilisation, the human zygote becomes a **blastula** (called a **blastocyst** in mammals). This is the early stage of embryonic development, when cell differentiation begins. Embryonic stem cells originate in the blastula and make up the primary **germ layers** (the **ectoderm**, **mesoderm** and **endoderm**) that differentiate to form specialised cells, tissues and organs in animals (Figure 4.3.2).

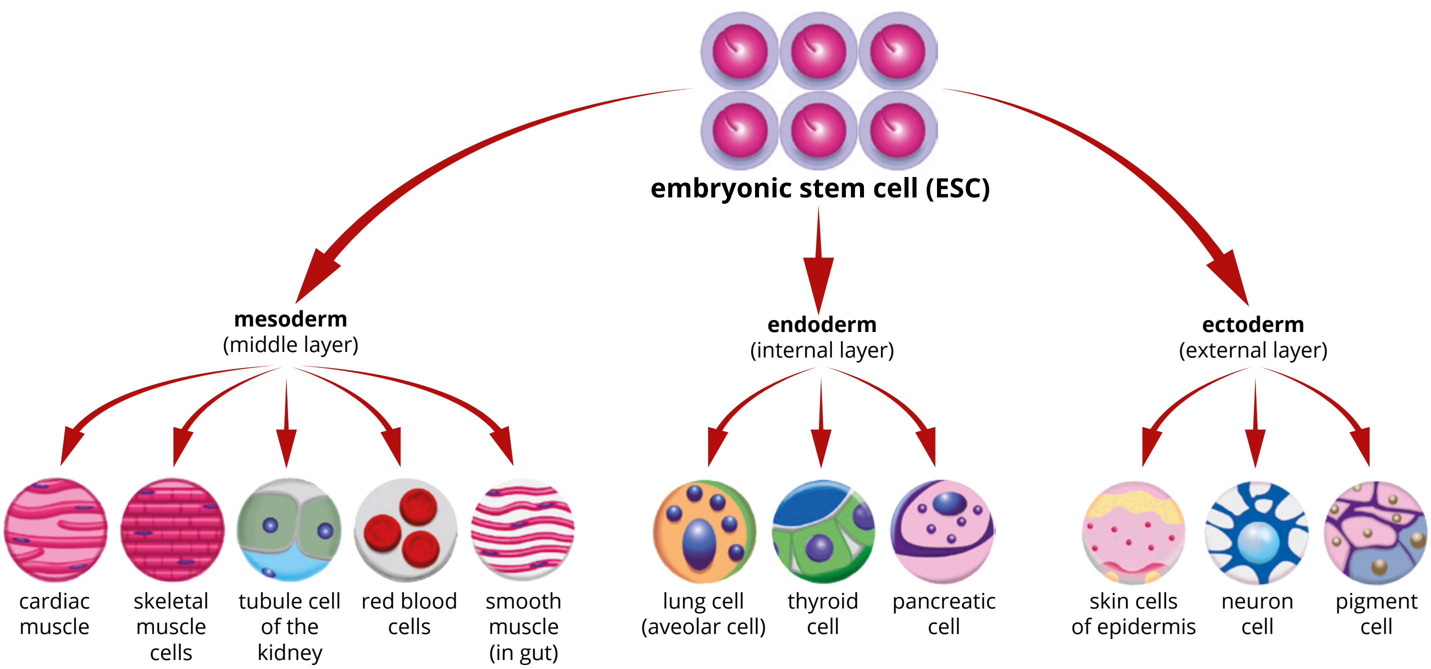


FIGURE 4.3.2 Embryonic stem cells produce every cell type required by the organism. In most multicellular organisms, stem cells make up three primary germ layers during embryonic development: the ectoderm, mesoderm and endoderm. The germ layers differentiate to form specialised cells, tissue and organs.

In plants, cell differentiation and cell specialisation derives from cells in the meristem tissue. The meristematic cells are unspecialised embryonic cells at the tips of shoots and roots (Figure 4.3.3). Organs such as leaves and flowers develop from cells in the shoot apical meristem, while root growth comes from the cells of the root apical meristem.

Unlike most animal cells, many cells in a plant's meristem tissue can continue differentiating and specialising throughout their entire life.

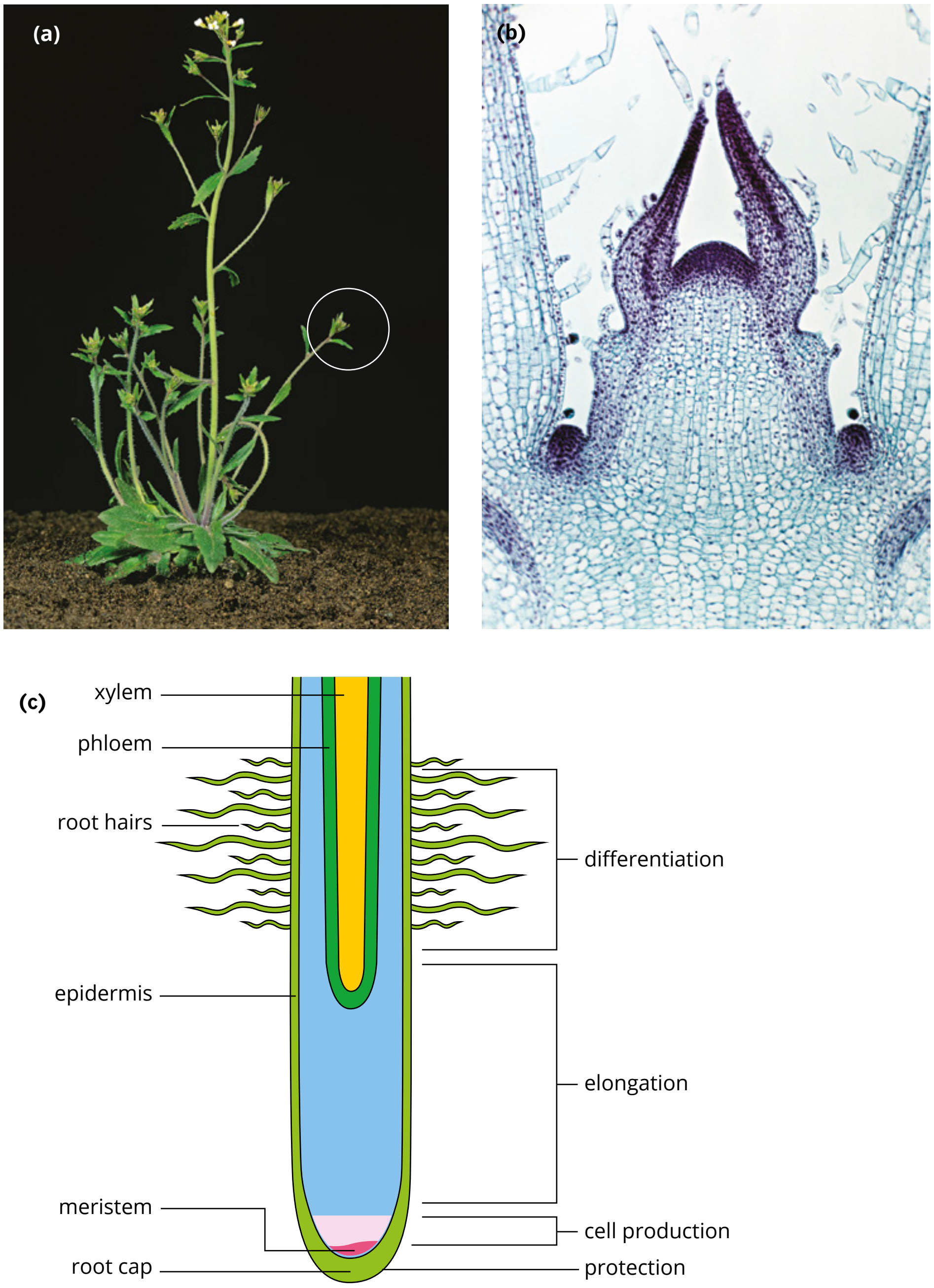
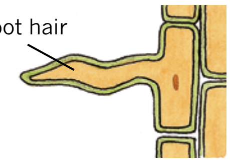
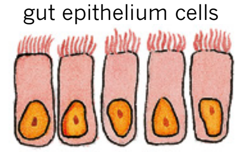
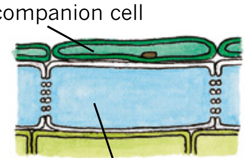
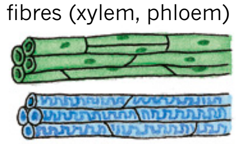
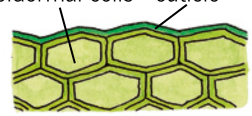
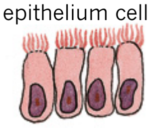
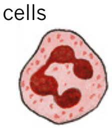
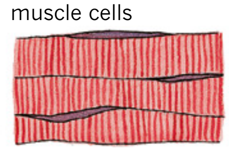
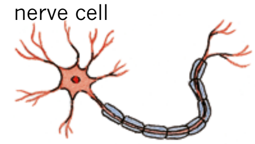


FIGURE 4.3.3 Plant cell production, growth and differentiation derives from unspecialised embryonic cells in the meristem, found in the tips of shoots and roots. (a) A thale cress (*Arabidopsis thaliana*) plant with the growing shoot tip highlighted. (b) Magnified image of stem cells in the shoot apical meristem. (c) The structures and regions of cell differentiation in the root meristem

The internal and external structure of a cell is the basis for the functions it performs. Examples of the structures and functions of specialised cells in plants and animals are shown in Table 4.3.1. Cell specialisation is an advantage, because cells are more efficient when they have only one function rather than many. This makes multicellular organisms much more energy efficient than unicellular organisms.

Cell specialisation is an advantage because it is more energy efficient to have cells that are specialised for one function, rather than many functions.

TABLE 4.3.1 The structure and function of some specialised cells in plants and animals

Cell function	Cell specialisation	
	Plant cells	**Animal cells**
exchange	root hair 	gut epithelium cells 
transport	companion cell  sieve cell	red blood cells 
strength/support	fibres (xylem, phloem) 	bone cells  cartilage cells 
protection/defence	epidermal cells cuticle 	ciliated epithelium cells  white blood cells 
photosynthesis	 mesophyll cells	
movement		muscle cells 
communication		nerve cell 

Specialised cells in animals include nerve cells, which are specialised to carry signals rapidly over long distances. They could not do this if they also had to break down food to obtain nutrients or protect against disease. Another example is a red blood cell, which is essentially a bag of haemoglobin that carries oxygen around the body. It cannot also protect the organism from an invading bacterium; this is the role of specialised white blood cells. In plants, different cells are specialised for photosynthesis, exchange of substances (with other cells or the environment) and fluid transport.

Gene expression

Gene expression is the process by which the information stored in **genes** is used to build the different structures in a cell. It determines how a cell will differentiate and function.

All the genes required to produce every type of cell needed by an organism are present in every cell after fertilisation. However, only some of these genes will be active (expressed) at any one time in different cells. For example, in developing red blood cells, the genes for haemoglobin are expressed, while in gland cells, genes that code for different hormones, such as insulin, are expressed.

In cancer cells, the genes that regulate normal cell growth and development have been altered. Scientists can observe these changes in gene expression using a technique called fluorescence microscopy. Fluorescent tags target specific genes, with the location and brightness of the fluorescence indicating the level of gene expression in different cells (Figure 4.3.4). Fluorescence microscopy is covered in more detail in Chapter 2.

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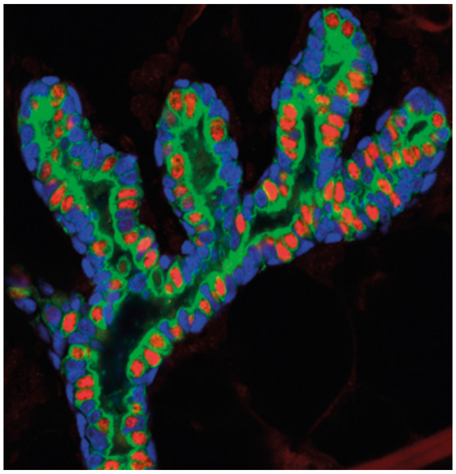


FIGURE 4.3.4 Fluorescence light micrograph of a human mammary gland showing gene expression. The blue fluorescence indicates a high level of expression of the *Sox10* gene, which is associated with breast cancer and high stem cell activity. The red fluorescence is the progesterone receptor, which indicates mature (non-stem cell) mammary cells. The green fluorescence is a protein called cytokeratin-8, which indicates mammary gland development.

> Different genes are expressed in different cells at different times. The genes that are expressed determine the structure and function of a cell.

An example of animal cell specialisation: your skin

The human body consists of about 210 different types of cells. Each of these cell types differentiates from unspecialised stem cells during embryonic development.

You learnt about the skin as an organ in Section 4.2. The skin's function relies on the many highly specialised cells within it. The epidermis alone has four different cell types: keratinocytes, Langerhans cells, Merkel cells and melanocytes (Figure 4.3.5). The cells of the epidermis also interact with many other cell types. Nerve cells, red and white blood cells, muscle cells and gland cells all contribute to the correct functioning of the skin cells in their role of protection, thermoregulation and sensation.

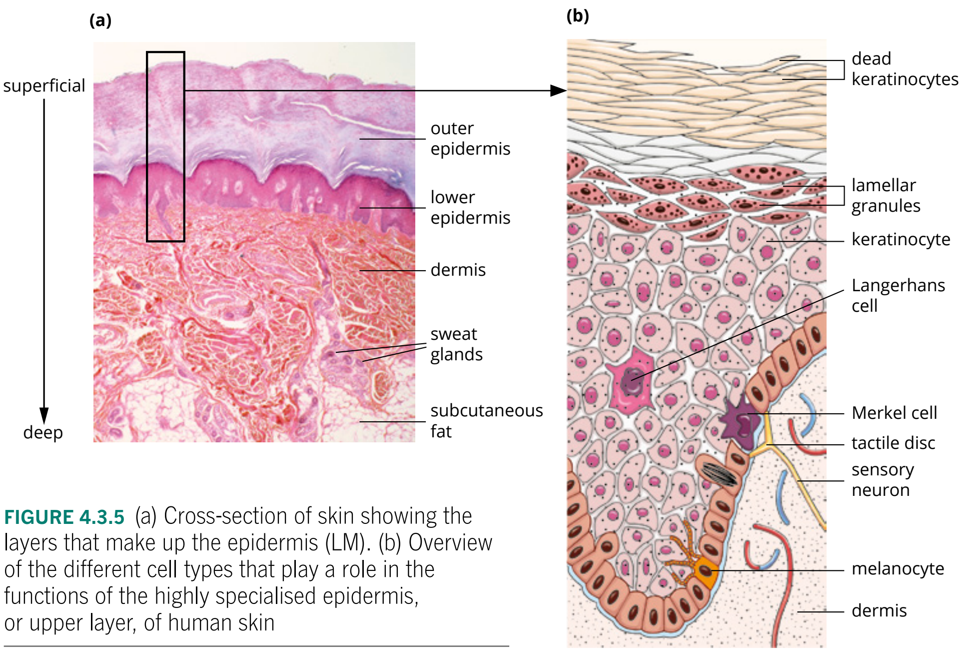


FIGURE 4.3.5 (a) Cross-section of skin showing the layers that make up the epidermis (LM). (b) Overview of the different cell types that play a role in the functions of the highly specialised epidermis, or upper layer, of human skin

The structures of specialised skin cells can give you clues about their function. The keratin-producing keratinocytes are the most common type of skin cell, making up around 90 to 95% of the epidermis. The flat, scale-like structure of keratinocytes (also called squamous cells) helps them maintain the structural integrity of the skin, with the tight junctions between them creating an effective barrier. Keratinocytes also interact with nerve cells, antigen-processing Langerhans cells, sensory-processing Merkel cells and melanin-producing melanocytes.

PA 2.1 PA 2.1 WS 2.3

BIOFILE CCT

Colourful courtship

Southern Australia is home to a colourful character, the giant cuttle (*Sepia apama*)—the largest cuttle in the world. The cuttles have two specialised cell types in their skin: one contains pigmented chromatophores, while the other has reflective iridophores. The chromatophores allow the cuttle to change skin colour, while the iridophores polarise light and produce iridescent colours with a reflective shine. Giant cuttles gather in large numbers in southern Australia between May and August each year for the breeding season. Their colour displays are an essential element of courtship behaviour (Figure 4.3.6).

FIGURE 4.3.6 Giant cuttles have specialised cells that change the colour, pattern and texture of their skin to attract a mate.

BIOLOGY IN ACTION DD IU

Sickle cell disease: Why does this disease persist?

Sickle cell disease is a disorder that is inherited when the HbS allele is passed from parents to offspring. It causes a chemical change in haemoglobin in red blood cells, making the haemoglobin molecules form long, rigid strands. This makes the red blood cells sickle-shaped (Figure 4.3.7). It also makes them inflexible, blocking small blood vessels and preventing sickle cells from transporting oxygen effectively. Normal red blood cells have a lifespan of about 120 days, but sickle cells often die within 20 days.

Sickle cell disease can result in anaemia, pain, fatigue and joint swelling. It can be fatal if left untreated. However, being a carrier for the condition can be advantageous in some parts of the world. People who are carriers have just one copy of the HbS allele. As a result, they have some red blood cells that function normally and some that are sickle-shaped. This means that they experience anaemia to a lesser extent. If these people live in a malaria-affected area, their sickle-shaped red blood cells offer them some resistance to malaria, because they are a poor host for the malaria parasite. This is one explanation for why sickle cell disease persists in some populations, even though it can have fatal consequences.

FIGURE 4.3.7 Two sickle cells (top) are visible next to the normal, biconcave-shaped red blood cells in this coloured SEM image.

4.3 Review

SUMMARY

- Cell replication and differentiation enable a single cell to produce the trillions of highly specialised cells that make up an organism.
- Cell differentiation is the process by which unspecialised cells, called stem cells, become specialised cells.
- Embryos have three primary germ layers: ectoderm, mesoderm and endoderm. These cell layers differentiate to form specialised cells, tissues and organs in animals.
- In plants, the stem cells are found in meristem tissue.
- Specialised cell function results from expression of certain sets of genes. This is called gene expression and is the process in which the information stored in genes is used to build the different cell structures.
- The internal and external structures of a specialised cell are related to the function it performs.
- Cell specialisation is an advantage, because cells are more efficient when they have only one function rather than many. This makes multicellular organisms much more energy efficient than unicellular organisms.

KEY QUESTIONS

1. What is the difference between a zygote and an embryo?
2. What is cell differentiation and why is it important for multicellular organisms?
3. What determines how a cell will differentiate and what functions it will perform?
4. Explain how cell differentiation differs in animal cells and plant cells.
5. Name the three germ layers that form from embryonic stem cells.
6. What is gene expression and how does it affect cell specialisation?
7. Name four specialised cells found in human skin.

Chapter review

04

KEY TERMS

blastocyst
blastula
cell
cell differentiation
cell replication
cell specialisation
colonial
colony
DNA (deoxyribonucleic acid)
ectoderm
embryo
endoderm
epidermis
evolution
facultative colony
fertilisation
gamete
gene
gene expression
germ layer
meristem
mesoderm
multicellular
obligate colony
organ
organelle
organism
ovum
pluricellular
reproduction
sperm
stem cell
system
tissue
unicellular
vascular tissue
zooid
zygote

REVIEW QUESTIONS

1 Why is the colonial theory thought to be the most likely mechanism by which multicellular organisms evolved and what evidence is there to support it?

2 Which of the following is not a characteristic of a multicellular organism?
- **A** Cells cooperate and communicate to function as a single organism.
- **B** Cells depend on each other for survival.
- **C** Organisms have specialised cells that are responsible for specific functions.
- **D** Different cell types contain different DNA.

3 Outline four differences between a unicellular and a colonial organism.

4 Explain why a Portuguese man-of-war is an example of an obligate colonial organism, and not a facultative colonial organism.

5 Which organisms are multicellular (M) and which are unicellular (U)?
- **a** *Paramecium* (protist)
- **b** bat (mammal)
- **c** earthworm
- **d** amoeba (protist)
- **e** diatom (protist)
- **f** human
- **g** yeast (fungi)
- **h** eucalypt tree (plant)
- **i** *Salmonella* (bacterium)
- **j** grasshopper

6 List five advantages of being multicellular.

7 Referring to your answers in Question 6, explain how being multicellular provides each of these advantages compared with unicellular organisms.

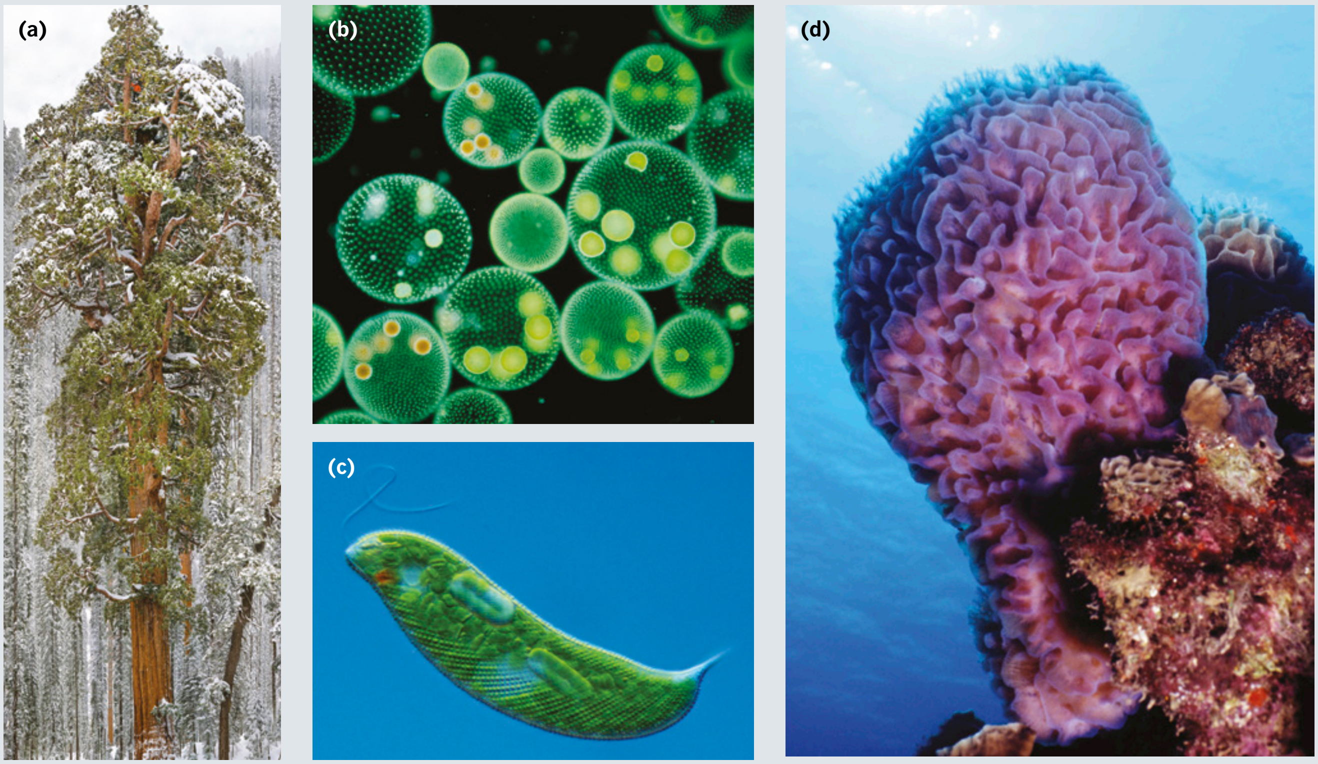
8 During the school holidays, you volunteer your time to assist a university student with some fieldwork. While out in the field, you come across a strange organism that you have not seen before. The organism is macroscopic and is made up of multiple cells. You observe that individual cells appear to be working together to sustain life. Based on your knowledge of unicellular, multicellular and colonial organisms, outline three other features would you expect of this organism.

9 Define each of the levels of organisation in multicellular organisms.

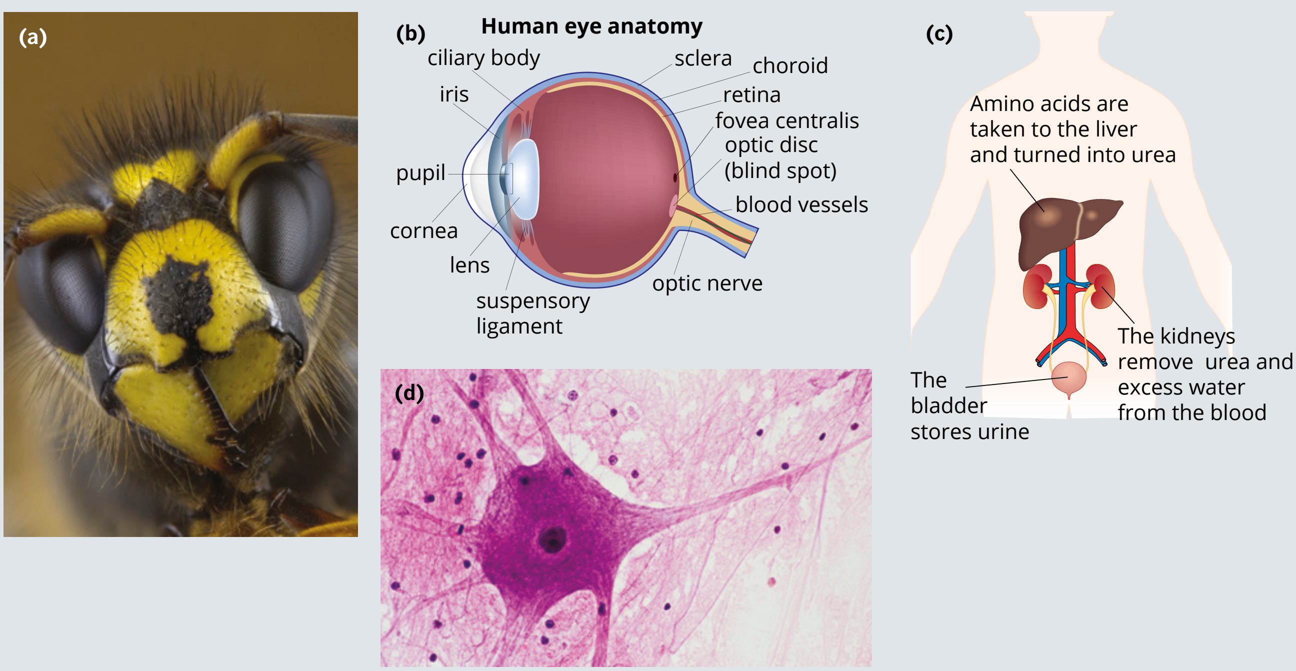
10 On the drive to school you are listening to a show on the radio about the Olympic Games. The radio presenter mentions that athletes need to maintain a constant level of fitness and that their muscles are their most important organ. Explain why muscles are not classified as an organ.

11 Identify the image that represents a:

a single cell
b simple colony
c multicellular organism without tissues
d multicellular organism with tissues, organs and systems.



12 State the level of organisation shown in each of the following images: tissue, organ, system or organism.



13 What level of cellular organisation are the following plant components classified as?
root
phloem
leaf
fruit
chloroplast
root hair cell
flower
xylem
shoot system

14 Create a flowchart that shows the levels of organisation in vascular plants and animals, indicating how these groups of organisms are similar.

15 List the advantages and disadvantages of developing organs on micro-devices.

16 Based on the advantages and disadvantages outlined in Question 15, write one paragraph that outlines your support or lack of support for developing organs on micro-devices.

17 Describe the process of cell differentiation and specialisation, mentioning at least four key terms from this chapter.

18 For each germ layer that forms during embryonic development, give an example of a cell type that is derived from it.

19 In humans, which skin layer is the outermost layer?
A meristem
B dermis
C epidermis
D subcutis

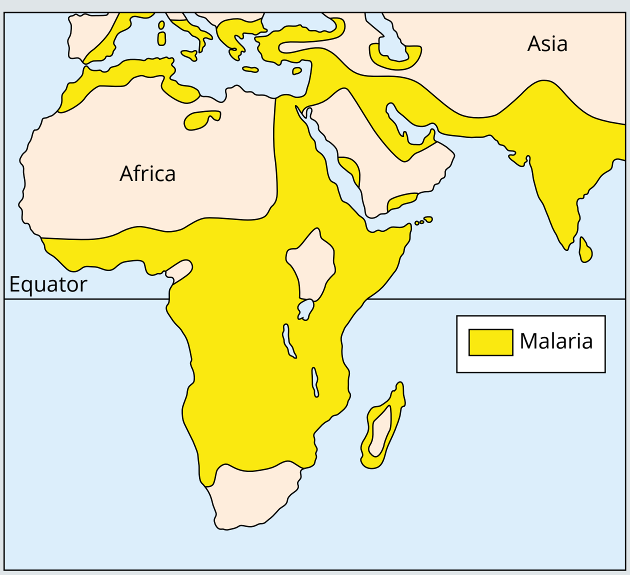
20 Match each specialised cell with its function.

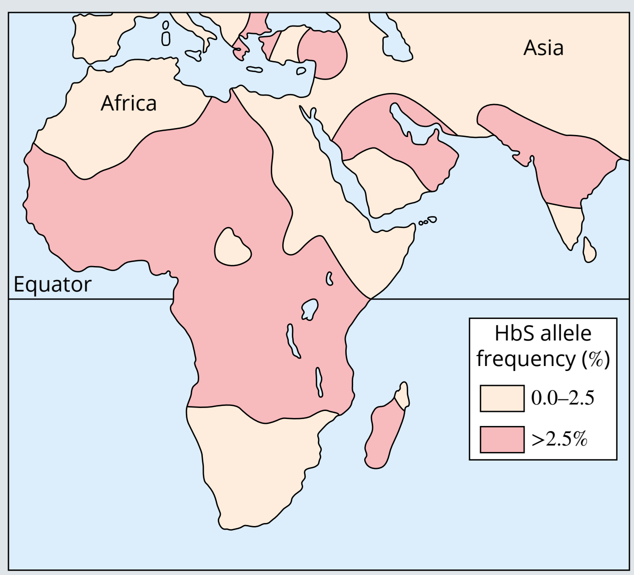
red blood cell	transports water
white blood cell	gives rise to specialised cells
nerve cell	increases surface area for uptake of water
guard cell	protects against pathogens
muscle cell	carries oxygen around the body
epidermal cell	forms a barrier against environmental stressors
meristem cell	carries signals around the body
xylem cell	allows movement of body parts
root hair cell	prevents water loss and regulates gas exchange

21 Explain how emperor penguins can dive to great depths for several minutes (sometimes longer) without needing to expel carbon dioxide.

22 Based on your explanation in Question 21, give examples of two animals that, in addition to the emperor penguin, may have the same adaptation as penguins to deep diving.

23 The following maps of Africa shows the distribution of malaria and the gene responsible for sickle cell disease (HbS allele).





Based on your knowledge of specialised cells, explain why there is an association between the distribution of malaria and the distribution of the gene responsible for sickle cell disease (HbS allele).

24 After completing the Biology Inquiry on page 194, reflect on the inquiry question: How are cells arranged in a multicellular organism? Explain how multicellularity has allowed for the evolution of complex biological structures.

CHAPTER

05 Nutrient and gas requirements

This chapter examines the division of organisms into those that can produce their own organic materials (autotrophs) and those that must consume the organic materials produced by others to meet their nutrient requirements (heterotrophs). You will investigate the structures that plants use to obtain nutrients and exchange gases by examining microscopic specimens and dissected plant material. The complex digestive and respiratory systems of mammals will be outlined, helping you to recognise different structures and their functions, and trace the digestion of foods as these particles move through the body.

Content

INQUIRY QUESTION

What is the difference in nutrient and gas requirements between autotrophs and heterotrophs?

By the end of this chapter you will be able to:

- investigate the structure of autotrophs through examining a variety of materials, for example: (ACSBL035) ICT
  - dissected plant materials (ACSBL032)
  - microscopic structures
  - using a range of imaging technologies to determine plant structure ICT
- investigate the function of structures in a plant, including but not limited to:
  - tracing the development and movement of the products of photosynthesis (ACSBL059, ACSBL060) ICT
- investigate the gas exchange structures in animals and plants (ACSBL032, ACSBL056) through the collection of primary and secondary data and information, for example:
  - microscopic structures—alveoli in mammals and leaf structure in plants ICT L
  - macroscopic structures—respiratory systems in a range of animals ICT L
- interpret a range of secondary-sourced information to evaluate processes, claims and conclusions that have led scientists to develop hypotheses, theories and models about the structure and function of plants, including but not limited to: (ACSBL034) CCT ICT L
  - photosynthesis
  - transpiration–cohesion–tension theory
- trace the digestion of foods in a mammalian digestive system, including: ICT L
  - physical digestion
  - chemical digestion
  - absorption of nutrients, minerals and water
  - elimination of solid waste
- compare the nutrient and gas requirements of autotrophs and heterotrophs ICT L

5.1 Autotroph and heterotroph requirements

Autotrophs make their own energy by converting inorganic matter to organic compounds. Autotrophs are also called producers because they produce all the organic compounds in an ecosystem.

In this section, you will learn how organisms are divided into groups according to how they fulfil their energy requirements, and how they use available resources to survive and thrive in their environments. You will also examine the nutrient and gas requirements of autotrophs and heterotrophs. Heterotrophs have a variety of complex feeding patterns based on their energy requirements, and the location and availability of resources.

Heterotrophs obtain organic compounds by consuming autotrophs or other heterotrophs. Because they consume organic compounds, they are also called consumers.

AUTOTROPHS

Autotrophs make their own **organic compounds** using energy and **inorganic compounds** from their environment, such as **carbon dioxide** and **water**. The process of converting inorganic carbon into organic compounds is called carbon fixation, because the autotroph 'fixes' the inorganic carbon into organic molecules such as **glucose** (Figure 5.1.1). These organic compounds are then consumed by **heterotrophs** (Figure 5.1.2). Figure 5.1.1 shows the flow of energy from autotrophs to heterotrophs in an ecosystem.

Carbon fixation is the process that living organisms use to incorporate carbon atoms into larger organic molecules.

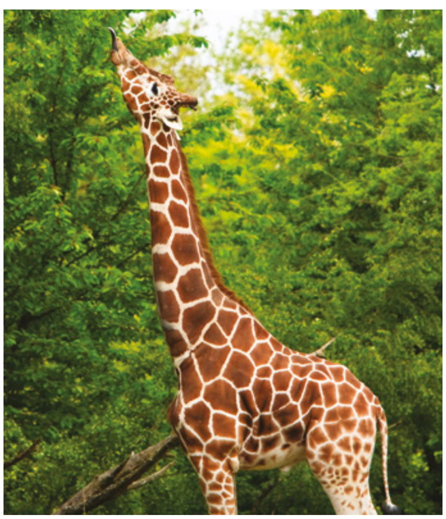


FIGURE 5.1.2 Although chemical nutrients can be recycled in an ecosystem, energy cannot be renewed. Instead, sunlight is used as an energy source to constantly convert inorganic matter such as carbon dioxide into organic matter by autotrophs (producers), which then feeds the heterotrophs (consumers). Without autotrophs, there would be no organic chemical energy in the ecosystem.

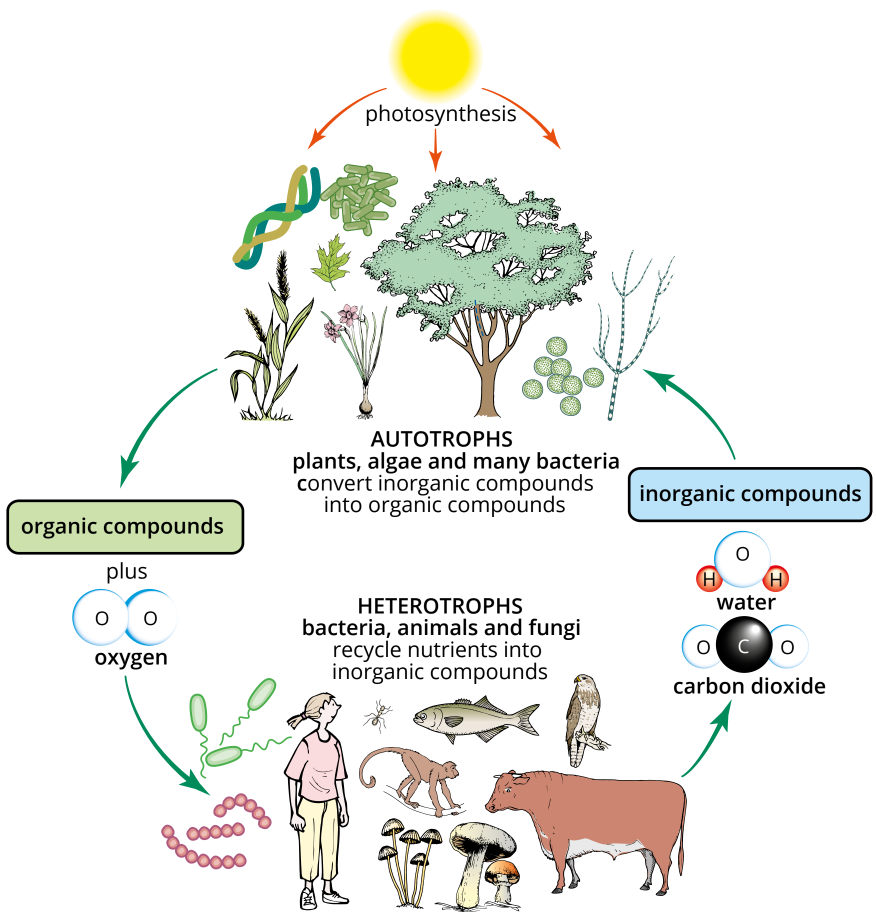


FIGURE 5.1.1 The cycling of matter through the environment, illustrating how autotrophs use energy and inorganic molecules to create organic molecules by carbon fixation. These organic molecules can then be consumed by heterotrophs to meet their energy requirements.

Autotrophs can be further divided into two groups according to how they obtain the energy required for carbon fixation. These two groups are:

- photosynthetic autotrophs, which use light energy (**photoautotrophs**)
- **chemosynthetic** autotrophs, which use chemical energy (**chemoautotrophs**).

Photosynthetic autotrophs

Photosynthetic autotrophs (photoautotrophs) are organisms that obtain the energy required for carbon fixation from light or solar energy (sunlight). They combine carbon dioxide and water using solar energy to produce organic compounds in a process known as **photosynthesis** (Figure 5.1.3). In plants, the organic compound produced by photosynthesis is glucose. The process of photosynthesis is covered in detail in Chapter 3.

Most autotrophs are photosynthetic. The most well-known photosynthetic organisms are green plants, but there are also other types of photosynthetic organisms, such as algae, *Euglena* and cyanobacteria (Figure 5.1.4).

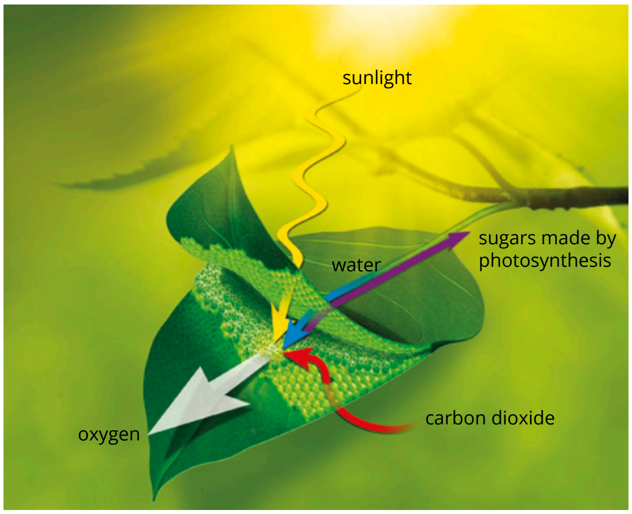


FIGURE 5.1.3 The inputs and outputs of photosynthesis in a leaf. Sunlight (yellow arrow) is used by photoautotrophs as an energy source to turn inorganic carbon dioxide and water into an organic energy source, glucose (sugar). Carbon dioxide (red arrow) enters the leaf and oxygen (white arrow) exits the leaf through pores, called stomata, in the leaf's lower surface. Water (blue arrow) and sugars (purple arrow) are transported through the plant via the stems and veins of the leaves.

Carnivorous plants, such as the Venus flytrap (*Dionaea muscipula*) (Figure 5.1.5), obtain some nutrients, such as nitrogen, potassium and phosphorous, by capturing and consuming other organisms. However, because they obtain most of their organic compounds through photosynthesis, they are considered photosynthetic autotrophs.

FIGURE 5.1.5 The Venus flytrap (*Dionaea muscipula*) is a carnivorous plant native to the United States. When hairs are triggered on the leaves, they snap shut to capture prey.

Protists are unicellular eukaryotic organisms that belong to the Kingdom Protista. Protists live in water and many of them are photosynthetic.

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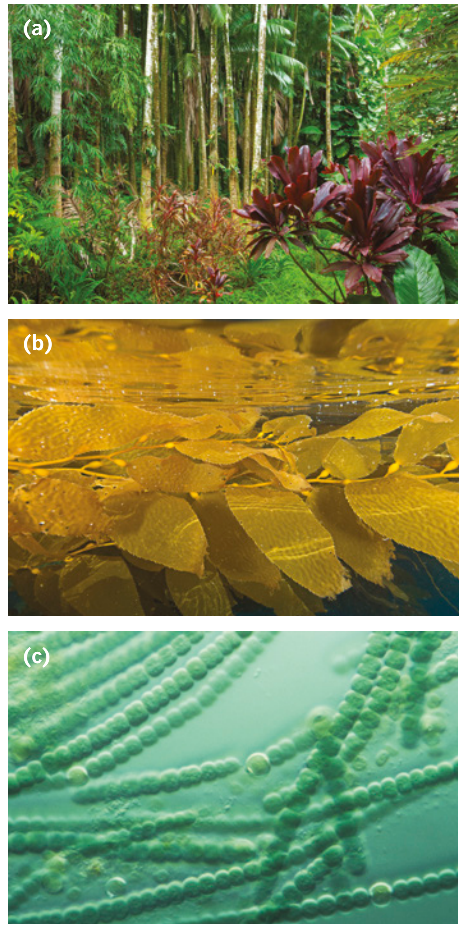

FIGURE 5.1.4 Photoautotrophs use light energy to make organic molecules from carbon dioxide and water. (a) On land, plants are the main photoautotrophs. In aquatic environments, the main photoautotrophs are (b) algae such as this kelp and (c) prokaryotes called cyanobacteria.

+ ADDITIONAL CCT N

Solar energy

The solar energy reaching Earth from our Sun is called electromagnetic radiation. The range of electromagnetic energy emitted by the Sun is known as the solar spectrum, and lies mainly in three regions: ultraviolet, visible, and infrared (Figure 5.1.6a).

The solar spectrum extends from about 0.29 μm (or 290 nm) in the longer wavelengths of the ultraviolet region, to more than 3.2 μm (3200 nm) in the far infrared region. Small amounts of radio waves are also given off by the Sun and other stars. While the Sun does emit ultraviolet radiation, most solar energy comes in the form of light and heat, in the visible and infrared regions of the electromagnetic spectrum.

Visible light spans the relatively narrow range of 0.4 to 0.9 μm (or 400 to 700 nm). The eye of humans and many other animals is a sensory organ that evolved to detect this part of the solar spectrum. The human eye perceives 400 nm radiation as violet, and 600 nm radiation as red.

The chlorophyll molecule in green plants absorbs ultraviolet and the visible light colours of blue, violet and red, using this energy for photosynthesis. Most of the green light in sunlight is reflected by leaves, making them appear green to our eyes (Figure 5.1.6b).

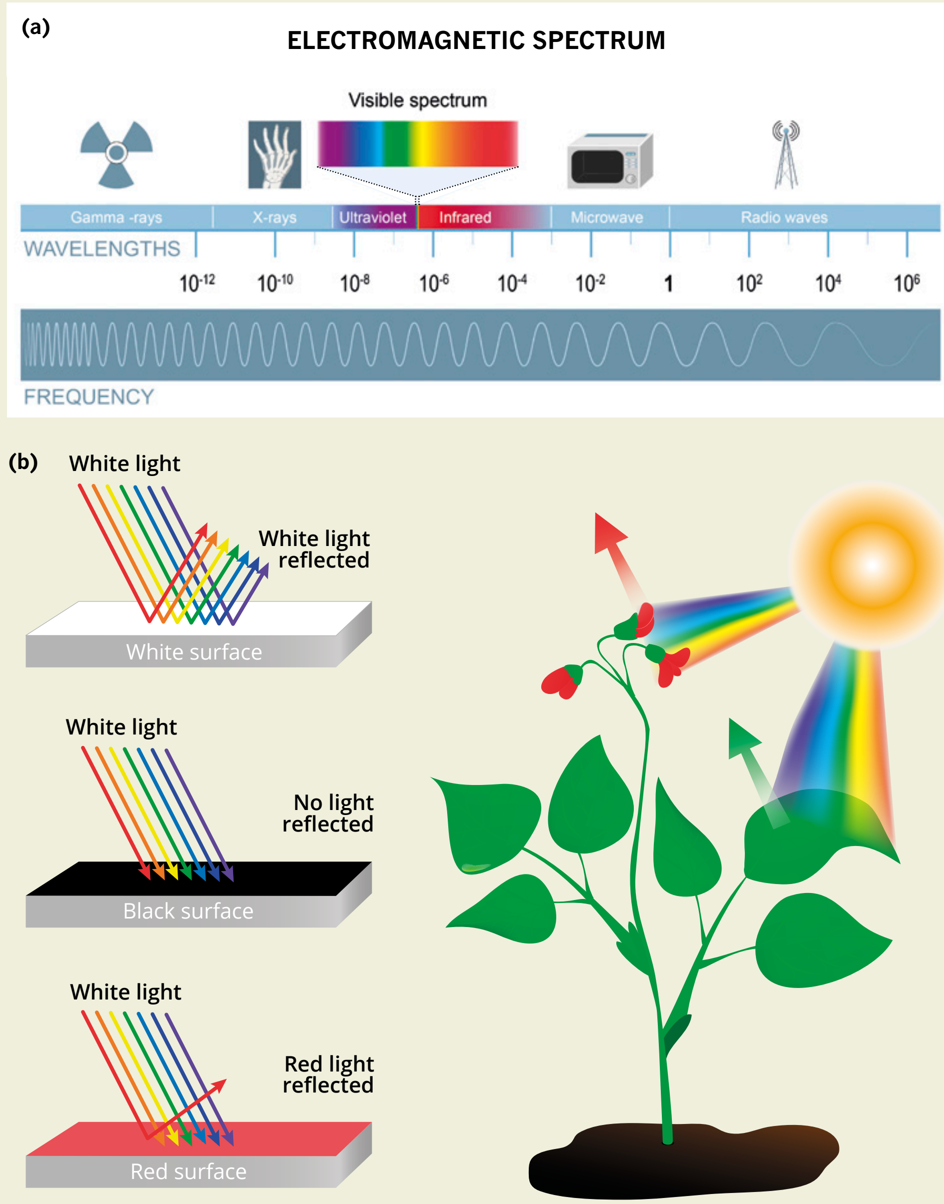

FIGURE 5.1.6 (a) The full range of electromagnetic waves shown in order of decreasing frequency and increasing wavelength from left to right. Most of the energy coming from the Sun is in the visible region of the electromagnetic spectrum, making up what we call sunlight (white light). Solar energy also includes IR (infrared) and some UV (ultraviolet). (b) The colour of an object is determined by which light waves it absorbs and which ones it reflects. Leaves reflect green light waves, making them appear green to our eyes, while the flowers in this diagram reflect red light. Blue, violet and red are the light waves used for photosynthesis.

Figure 5.1.7a shows that the rate of photosynthesis is highest under red light (between 650 and 700 nm). The rate of photosynthesis is also high under blue and violet light (between 400 and 450 nm). The lowest rate of photosynthesis occurs under green light (between 500 and 600 nm).

Figure 5.1.7b shows the amount of light that is absorbed by different chlorophyll molecules: chlorophyll *a*, chlorophyll *b* and chlorophyll *c*. Different types of chlorophyll have slightly different molecular shapes and so absorb light of different wavelengths. Chlorophyll absorbs many of the colours that make up the spectrum of white light, but reflects green light. The spectrum in Figure 5.1.7b shows that red, blue and violet light are all strongly absorbed, while yellow is absorbed to a lesser extent and green is not absorbed at all.

Several types of chlorophyll are found in photosynthetic organisms:

- Chlorophyll *a* is found in all photosynthetic organisms.
- Chlorophyll *b* is found in some plants.
- Chlorophyll *c* is found in algae.
- Chlorophyll *d* and *f* are found in cyanobacteria.

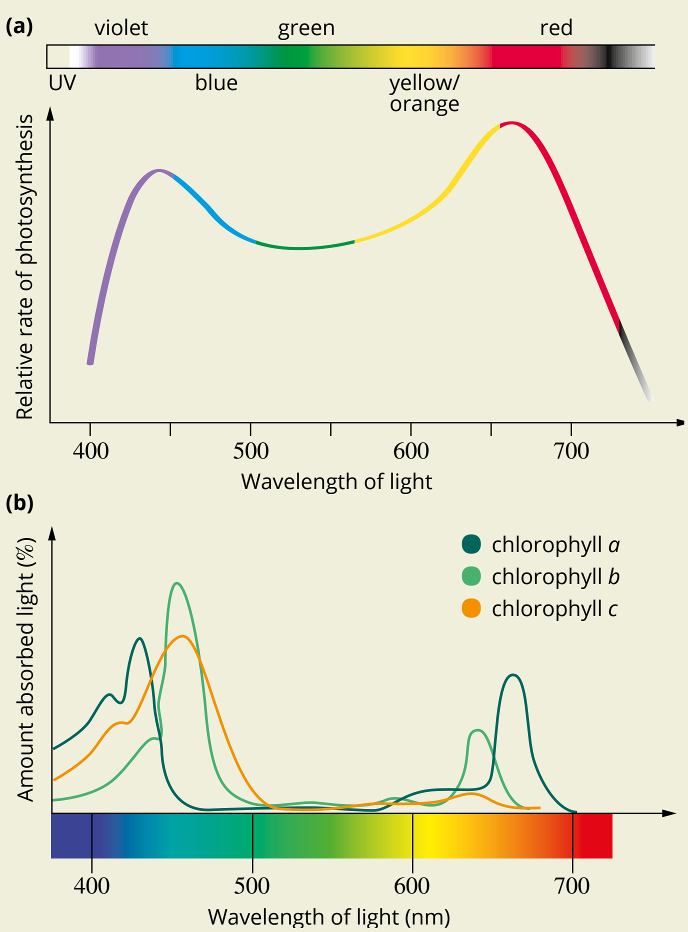

FIGURE 5.1.7 (a) The rate of photosynthesis occurs at different rates in different wavelengths of light. The pattern of photosynthetic activity is similar to (b) the absorption spectrum of chlorophyll.

SKILLBUILDER N

Transforming decimal notation to scientific notation

Scientists use scientific notation to handle very large and very small numbers.

For example, instead of writing 0.000 000 035, scientists would write 3.5×10^{-8}.

A number in scientific notation (also called standard form or power of 10 notation) is written as

$a \times 10^n$

where

a is a number equal to or greater than 1 and less than 10, that is $1 \leq a < 10$

n is an integer (a positive or negative whole number)

n is the power that 10 is raised to and is called the index value.

To transform a very large or very small number into scientific notation:

1. Write the original number as a decimal number greater than or equal to 1 but less than 10.
2. Multiply the decimal number by the appropriate power of 10.

The index value is determined by counting the number of places the decimal point needs to be moved to form the original number again.

- If the decimal point is moved *n* places to the right, *n* will be a positive number. For example: $51 = 5.1 \times 10^1$
- If the decimal point is moved *n* places to the left, *n* will be a negative number. For example: $0.51 = 5.1 \times 10^{-1}$

You will notice from these examples that when large numbers are written in scientific notation, the 10 has a positive index value. Very small numbers are written with 10 to a negative index.

Chemosynthetic autotrophs

Chemosynthetic autotrophs obtain the energy they need for carbon fixation from inorganic chemical reactions—a process known as chemosynthesis. All known chemosynthetic organisms are prokaryotes.

Some chemosynthetic autotrophs obtain energy by the oxidation of inorganic molecules. Some of these conversions include:

- ammonium ions (NH_4^+) to nitrite ions (NO_2^-)
- nitrite ions (NO_2^-) to nitrate (NO_3^-)
- sulfide ions (S_2^-) to sulfate ions (SO_4^{2-}).

FIGURE 5.1.8 Wetlands such as these are commonly home to many chemoautotrophic methanogens.

Chemoautotrophs can live in the more extreme environments where these ions can be found. For this reason, these organisms are often referred to as extremophiles. **Methanogens** are chemoautotrophs that live in environments where hydrogen is more readily available. They obtain energy from a carbon-fixing reaction in which carbon dioxide (CO_2) and hydrogen (H_2) react to form a simple organic compound: methane (CH_4). Methanogens are poisoned by **oxygen** and live in places with very low oxygen levels, such as in the digestive tracts of animals and in wetlands (Figure 5.1.8).

Other chemoautotrophs include:

- archaea that live off the carbon in coal (Figure 5.1.9a)
- bacteria that convert sulfur to sulfate in deep sea thermal vents
- various nitrifying bacteria that fix nitrogen gas from the air or convert ammonia to nitrite to nitrate ions underground, helping plant growth in the process (Figure 5.1.9b)
- denitrifying bacteria that return nitrogen to the air
- rock-eating bacteria that obtain energy from hydrogen in rock compounds and dissolved carbon dioxide in water trapped deep underground (Figure 5.1.9c)
- iron-oxidising bacteria located in lava beds and groundwater that form a sludge of reddish-brown iron rust
- bacteria that decompose crude oil.

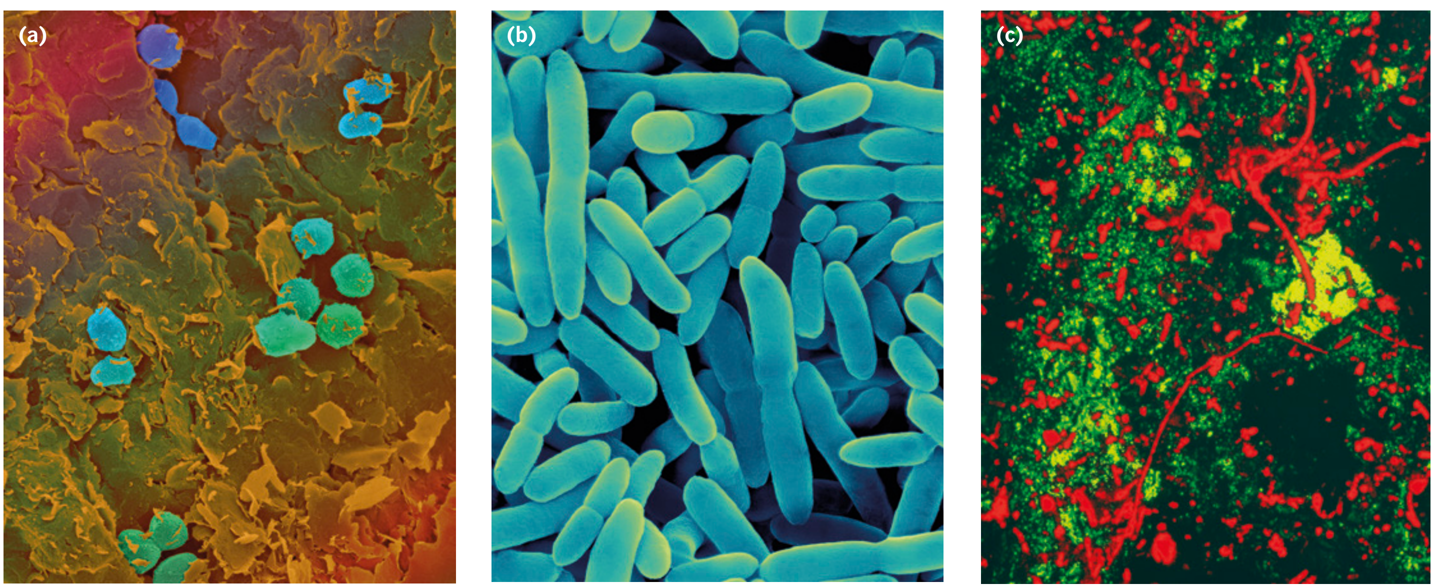

FIGURE 5.1.9 (a) Coal-degrading archaea. Carbon is a food source for these microorganisms and methane is the waste product. Scanning electron micrograph (SEM), magnification: ×4000. (b) Nitrifying bacteria (*Nitrobacter* sp.) turn nitrogen-based nitrite compounds into nitrate–the second step of nitrification. These microorganisms live in soil, sewage and freshwater and marine environments. SEM, magnification: ×2200. (c) Rock-eating bacteria (red) are some of the first known life forms that do not depend on energy from the Sun. These bacteria are thought to obtain energy from carbon (yellow) and hydrogen in rock (green).

BIOLOGY IN ACTION CCT IU

Radiotrophs

Radiotrophic fungi and bacteria are rare types of autotroph that use nuclear radiation as their source of energy, rather than light or chemical energy. They have the potential to be used for cleaning up and stabilising radioactive contamination.

Radiotrophic bacteria

In 2015, a strain of betaproteobacteria was found in soil at an old uranium mine in Colorado. The bacteria were sourcing their energy from the radioactive uranium (Figure 5.1.10). Research continues into how they could be used to prevent uranium waste from contaminating groundwater. Bacteria that are chemosynthetic for iron are often radiotrophic for uranium as well.

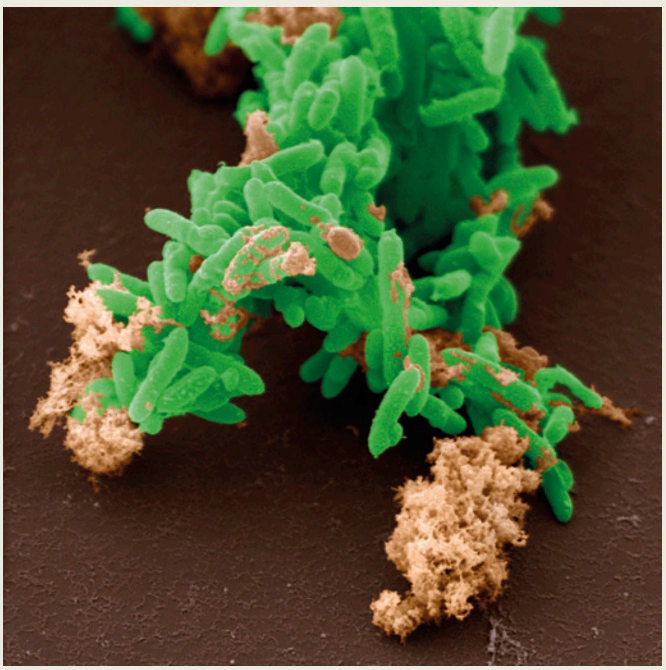

FIGURE 5.1.10 A coloured SEM image of radiotrophic bacteria that live without oxygen and gain their energy from digesting uranium

Radiotrophic fungi

In 1991, scientists discovered a black mould growing on the walls inside the abandoned Chernobyl nuclear power plant in Ukraine. This was the site of the 1986 Chernobyl disaster, which is regarded as the worst nuclear power plant accident in history. The area surrounding the power plant is highly contaminated with radiation and has mostly been abandoned by humans. In the absence of people, a forest has grown and the area has been recolonised by wildlife (Figure 5.1.11).

FIGURE 5.1.11 The abandoned Chernobyl nuclear power plant and surrounding town are now also home to a forest.

The mould was identified as *Cladosporium sphaerospermum*, a radiotrophic fungus. Radiotrophic fungi use radiation that is lethal to other organisms as a source of energy (Figure 5.1.12). They are usually dark in colour, because they contain a dark pigment called melanin, which they can use to convert the radiation into chemical energy. This energy is then used to make organic compounds.

Researchers have found that these fungi can grow much faster when exposed to high levels of radiation. It is not yet clear whether these fungi use a process similar to photosynthesis or chemosynthesis. But because light is a kind of radiation, it seems likely that they use a process similar to photosynthesis.

Although radiotrophic fungi are common in environments where radiation levels are normal, they also thrive in places where higher levels of radiation occur naturally, such as Antarctica and high-altitude regions.

FIGURE 5.1.12 High levels of radiation around the Chernobyl disaster site provide the ideal environment for *Cladosporium sphaerospermum* to flourish.

HETEROTROPHS

FIGURE 5.1.13 The purple swamphen (*Porphyrio porphyrio*) eats the seeds and soft stems of reeds, and the snails that feed on the reeds.

Unlike autotrophs, heterotrophs cannot carry out carbon fixation using light or chemical energy, and cannot use simple inorganic substances to make organic compounds. Instead, they obtain organic compounds by consuming other organisms or their products (Figures 5.1.13 and 5.1.14). Heterotrophs use the nutrients they consume to obtain their energy.

All heterotrophs depend directly or indirectly on autotrophs for nutrients and energy. For example, a swamphen eating a soft plant stem is using an autotroph directly as a food source. That swamphen might also eat an insect that feeds on the plant, and so also depends indirectly on the plant for food.

All animals and fungi are heterotrophs. Some bacteria and many protists are also heterotrophs. Because most heterotrophs feed on certain types of organisms (e.g. plants or animals), they can be further subdivided into groups based on their diet.

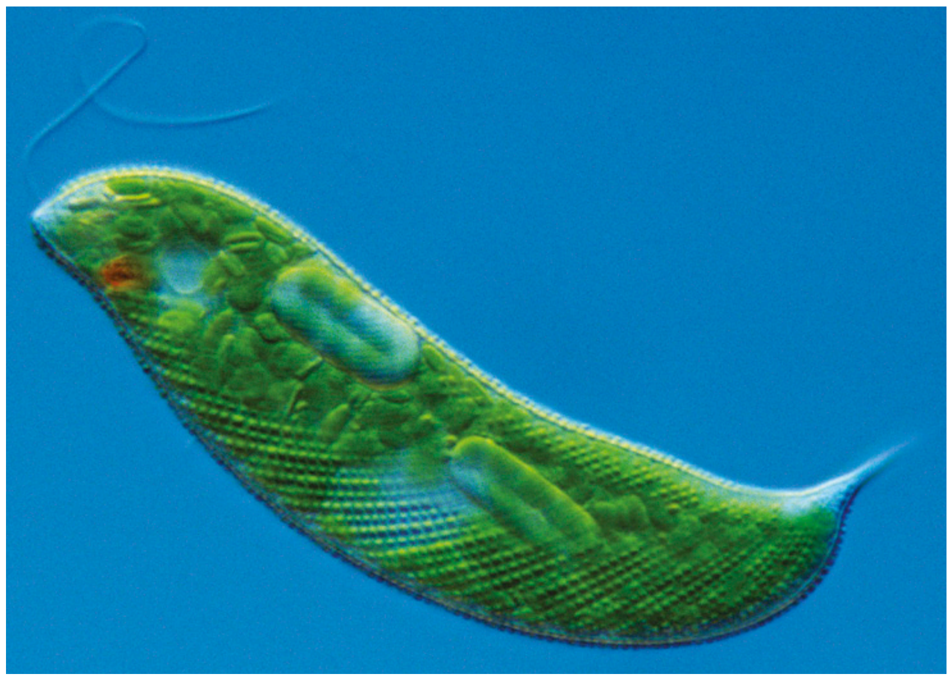

FIGURE 5.1.14 *Euglena* species are single-celled flagellate protists that can obtain energy from both sunlight and other organisms. They have the rare ability to be autotrophic or heterotrophic. In sunlight, *Euglena* protists are photoautotrophs. But when there is no sunlight, they can absorb food from their environment, so they are also heterotrophic.

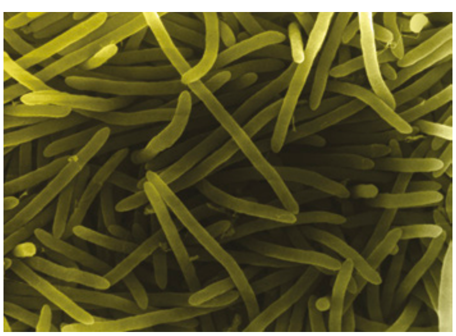

FIGURE 5.1.15 Heliobacteria are terrestrial organisms that convert solar energy into chemical energy, but must still obtain their carbon from organic sources. This makes them photoheterotrophs, not autotrophs, because autotrophs fix carbon from inorganic CO_2.

Photoheterotrophs

Photoheterotrophs are specialised prokaryotes that use solar energy, rather than organic compounds, as a source of energy. Unlike photoautotrophs, photoheterotrophs cannot fix carbon from CO_2 into organic compounds such as glucose. They use organic compounds obtained from other organisms as their carbon source for growth and renewal, not as an energy source. Photoheterotrophic organisms include green non-sulfur bacteria, purple non-sulfur bacteria and heliobacteria (Figure 5.1.15).

Chemoheterotrophs

Most heterotrophs are **chemoheterotrophs**. They obtain energy from organic compounds by a chemical conversion called **cellular respiration**. Animals, protists, fungi and most heterotrophic bacteria are chemoheterotrophs. The chemoheterotrophs can be further divided by their source of food.

Herbivorous heterotrophs

Herbivorous heterotrophs are animals that eat only plant material, and are known as **herbivores**. Kangaroos, horses, parrots, caterpillars and snails are all herbivores (Figure 5.1.16). Herbivores are examined in more detail in Section 5.3.

FIGURE 5.1.16 Caterpillars obtain their energy by eating only plant material. This makes them herbivorous heterotrophs.

FIGURE 5.1.17 Crocodiles are carnivorous heterotrophs that obtain their energy by eating other animals.

Carnivorous heterotrophs

Carnivorous heterotrophs are animals that eat only other animals, and are known as **carnivores**. Dingoes, eagles, crocodiles, sharks and spiders are all carnivores (Figure 5.1.17). Carnivores are examined in more detail in Section 5.3.

Omnivorous heterotrophs

Omnivores are organisms with a broad diet that can eat a mixture of both plants and animals. This distinguishes them from carnivores, which eat only animals, and herbivores, which eat only plants. Omnivores don't tend to specialise in a food source, but instead are opportunistic eaters, eating foods that are easily available to them. Humans, bears, and lizards such as the blue-tongued skink (Figure 5.1.18) are all omnivorous. Omnivores are examined in more detail in Section 5.3.

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FIGURE 5.1.18 An eastern blue-tongued skink (*Tiliqua scincoides scincoides*) eating a snail. The eastern blue-tongued skink is a subspecies of the common blue-tongued skink (*Tiliqua scincoides*), which is common throughout eastern Australia. Blue-tongued skinks are omnivorous, consuming foods such as berries, flowers, snails and beetles.

FIGURE 5.1.19 This saprotrophic mould (white 'fluff') is breaking down the strawberry to obtain nutrients.

Saprotrophic heterotrophs

Another group of heterotrophs are the **saprotrophs**, which include most fungi and some bacteria. Saprotrophs eat by digesting organic material by extracellular means. This means they secrete enzymes onto dead and decaying organic material, such as carcasses, leaf litter or fruit (Figure 5.1.19). Once the enzymes have broken down the large molecules, the saprotrophic organisms absorb the simple organic nutrients through endocytosis. This process of decomposing and recycling organic matter is essential for ecosystems to function, because the process returns nutrients back into the environment to continue driving the cycle of energy.

Parasites

Parasitic heterotrophs, or **parasites**, derive their energy and nutrients directly from other living organisms. They feed on the cell contents, tissues or body fluids of their host. The host is usually harmed and sometimes even killed in the process. Parasites are highly diverse and can be found in all five kingdoms. Parasites that live inside the host are called endoparasites, and include tapeworms and liver flukes. Parasites that live outside the host are called ectoparasites, and include ticks and lice (Figure 5.1.20).

FIGURE 5.1.20 A head louse (*Pediculus humanus capitis*) crawling on human hairs. Head lice are ectoparasites that live only on human scalps. They bite through the skin to feed on blood, which is a rich and concentrated source of nutrients and energy that sustains them for their entire life cycle.

COMPARING HETEROTROPHS AND AUTOTROPHS

Table 5.1.1 summarises the division of heterotrophs and autotrophs according to how they acquire energy and carbon.

WS 2.4

TABLE 5.1.1 Heterotroph and autotroph energy and carbon sources

Type of organism	Energy source	Carbon source
photoautotroph	solar energy (sunlight)	carbon dioxide
chemoautotroph	inorganic molecules	carbon dioxide
photoheterotroph	solar energy (sunlight)	organic compounds
chemoheterotroph	organic compounds	organic compounds

5.1 Review

SUMMARY

- Autotrophs use energy and inorganic molecules from the physical environment to produce the organic compounds they need.
- Most autotrophs, including plants and algae, are photosynthetic. That is, they use solar energy for producing energy-rich organic compounds.
- Some autotrophs, including some bacteria and archaea, are chemosynthetic, meaning they obtain energy by carrying out energy-releasing reactions between inorganic molecules.
- Heterotrophs, including animals, fungi and some bacteria and protists, obtain organic compounds by eating other organisms or their products.
- Herbivorous heterotrophs obtain their energy by eating plant matter.
- Carnivorous heterotrophs obtain their energy by eating animal matter.
- Omnivorous heterotrophs obtain their energy by eating both plant and animal matter.
- Saprotrophic heterotrophs obtain their energy by digesting organic material by extracellular means. This means they secrete enzymes onto dead and decaying organic material and absorb the simple organic nutrients through endocytosis.
- Parasitic heterotrophs obtain their energy and nutrients by feeding on the cell contents, tissues or body fluids of their hosts.

KEY QUESTIONS

1 Phytoplankton are autotrophs.
  a Are they photoautotrophs or chemoautotrophs?
  b How do they obtain energy?
  c What kind of environment do they live in?

2 Which one of the following is an example of chemosynthesis?
  A glucose production by plants
  B methane production by methanogens
  C carbon dioxide production by organisms
  D conversion of nitrites into nitrates by prokaryotes

3 *Euglena* is both a heterotroph and an autotroph. Explain why.

4 Give an example of how heterotrophs rely both directly and indirectly on autotrophs.

5 What kind of heterotroph are humans? Explain your answer.

6 Contrast the way in which carnivores and saprotrophs obtain their organic compounds, giving an example of each type of organism.

5.2 Autotroph nutrient and gas exchange systems

BIOLOGY INQUIRY ICT

Comparing autotrophs and heterotrophs

What is the difference in nutrient and gas requirements between autotrophs and heterotrophs?

PART A: Measuring autotroph requirements using a potometer

COLLECT THIS...

- a plant cutting
- a device to measure transpiration (e.g. a potometer)

DO THIS...

1 Set up your potometer using Figure 5.2.1 as a guide. A potometer is a device that is used to estimate transpiration rates by measuring the rate of water loss or uptake by the plant.
2 Measure the change in meniscus line level every 5 minutes for 30 minutes, recording your results in an appropriate table. The movement of water in the tube provides an estimate of the water uptake of the plant.

RECORD THIS...

Describe what happened to the meniscus level over the 30 minute period.

Present a hypothesis predicting what would happen if the humidity (moisture in the air) increased while measuring transpiration rates.

FIGURE 5.2.1 A potometer is a device used to measure the rate of water uptake in a plant. It can be a useful indicator of transpiration rates.

PART B: Measuring heterotroph requirements using a spirometer

In humans, ventilation is the movement of air between the lungs and external environment. Ventilation changes in response to levels of physical activity, as the body's energy demands are increased or decreased. These changes can be detected using a device called a spirometer. A spirometer measures the amount (volume) and/or speed (flow) that air is inhaled and exhaled (Figure 5.2.2). It is commonly used to assess people for lung disorders.

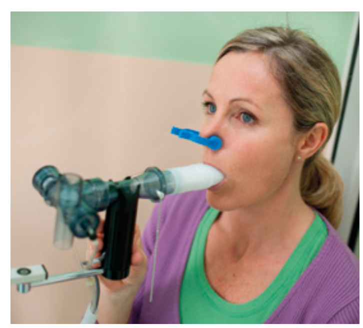

FIGURE 5.2.2 A patient blows into a spirometer during a test to assess lung health.

COLLECT THIS...

Depending on the resources available in your school laboratory, this task can involve monitoring ventilation in different ways:

- via simple observation—counting number of breaths per minute
- chest belt and pressure monitor—recording the rise and fall of the chest
- spirometer—recording the volume of gas exhaled per breath

DO THIS...

1 Working in pairs, set up your ventilation apparatus.
2 Measure and record the ventilation rate of you and your partner when at rest.
3 Have one person in your pair run on the spot for 1 minute.
4 Measure and record their ventilation rate after exercising.
5 Repeat steps 3 and 4 for the other person in your pair.

RECORD THIS...

Describe what happened to your ventilation rate after exercising.

Present your results in a line graph and share it with the class.

REFLECT ON THIS...

What is the difference in nutrient and gas requirements between autotrophs and heterotrophs?

What would happen to the rate of transpiration if the environmental conditions of an autotroph changed?

Why do the gas requirements of heterotrophs increase during exercise and decrease after exercise?

This section introduces you to the structures of a plant that are involved in obtaining nutrients and exchanging gases. The structure of a plant appears quite simple at first. But by delving deeper to the microscopic level, you will see that just like animals, plants are very complex organisms. The vascular tissue of a plant contains specialised cells and vessels for transporting materials from roots to leaves and all around the plant (Figure 5.2.3). This section allows you to explore the microscopic structure of leaves, stems and roots, which are essential for nutrient exchange. Photosynthesis is also discussed, allowing you to recognise the inputs and outputs required for successful gas exchange.

FIGURE 5.2.3 The veins in a leaf are vascular tissue, which is specialised for transporting water and organic solutes throughout the plant. Each vein is made up of a vascular bundle of xylem, phloem and a lignin sheath.

GAS EXCHANGE STRUCTURES

The ability of a plant to exchange gases with the environment is a vital element for its survival. Photosynthesis depends on interconnected variables, such as the amount of sunlight, water and carbon dioxide in a plant's environment. The exchange of gases via plants and animals is a reciprocal relationship; both organisms survive because of each other. Plants have many specialised structures that allow them to efficiently exchange gases with their envrionment.

FIGURE 5.2.4 This coloured SEM of a tobacco leaf shows one open stoma (centre) and one closed stoma (left). When the stoma is open, gas exchange can occur and water molecules can escape.

Stomata

Gas exchange in plants occurs through a structure called the **stoma** (plural stomata) (Figure 5.2.4). The stoma is the opening to an air space located in the lower epidermis of a leaf (Figure 5.2.5). Each stoma consists of two highly specialised epidermal cells called **guard cells**. The guard cells surround a pore, creating an opening through the epidermis and cuticle.

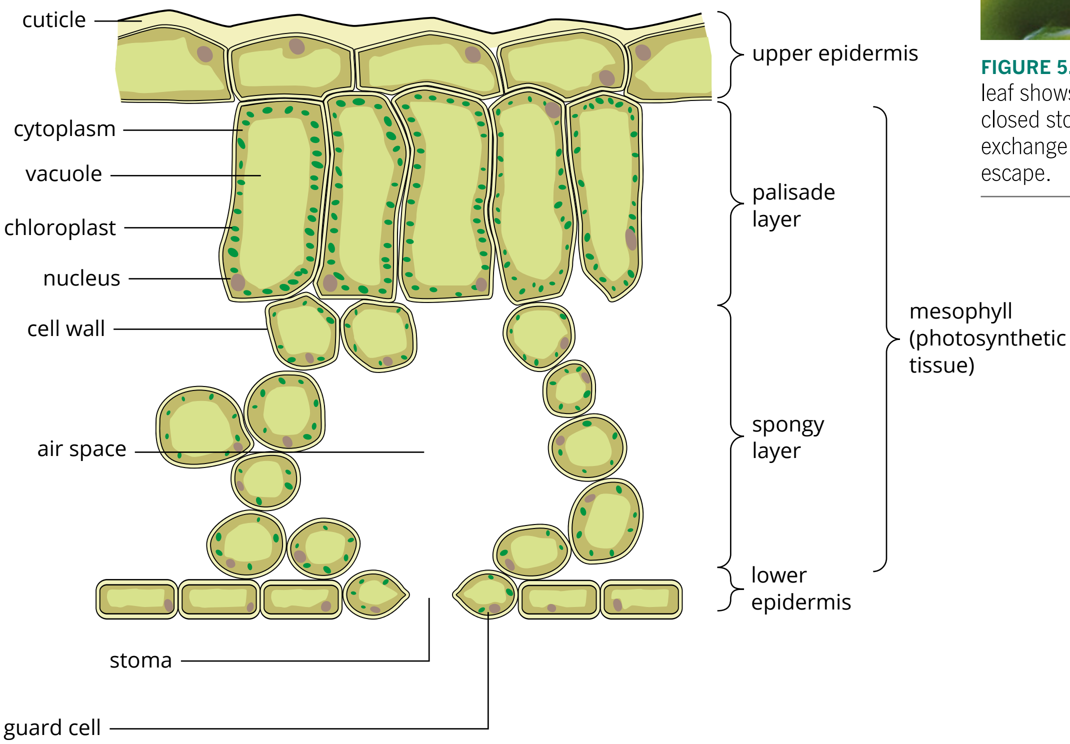

FIGURE 5.2.5 The arrangement of specialised cells in leaf tissue

Plants conduct gas exchange through stomatal pores in their leaves.

Stomata play an important role in regulating the exchange of gases and water between a plant's internal and external environment. They do this by changing shape, which causes the pore to open and close. When plants open their stomata to allow carbon dioxide gas in for photosynthesis, oxygen gas is released, and water is lost as water vapour during the process of **transpiration**. Transpiration is the passive movement of water through a plant from the roots and its evaporation as water vapour through the stomatal pores in leaves. Transpiration involves the upwards movement of water against the force of gravity. The theory that explains this phenomenon is called the **transpiration–cohesion–tension theory**. The process of transpiration and the transpiration–cohesion–tension theory are covered in detail in Chapter 6.

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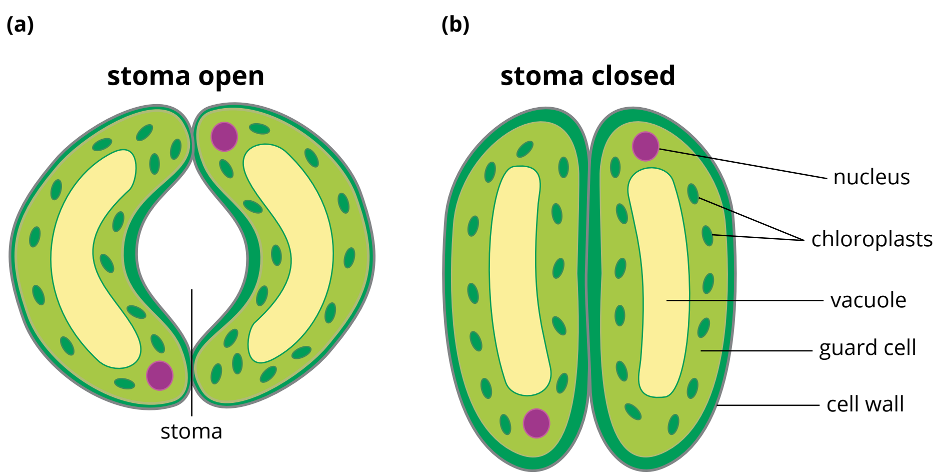
Stomata are usually open during the day to increase the rate of photosynthesis when sunlight is available. When the guard cells are **turgid**, or swollen, the stomatal opening is large, allowing water and gases to enter and exit the leaf (Figure 5.2.6a). The guard cells become swollen when potassium ions (K^+) accumulate and the water potential of the guard cells decreases. When guard cells lose water, the cells become **flaccid** and the stomatal opening closes, preventing water and gas from leaving the leaf (Figure 5.2.6b). The stomata close when light levels drop and the plants do not need any more carbon dioxide gas for photosynthesis.



WS 5.2

FIGURE 5.2.6 Stomata in the leaves of plants open (a) and close (b) to regulate gas exchange between the plant and its environment.

Chloroplasts

In the cells of eukaryotic autotrophs, photosynthesis occurs in the **chloroplasts**. Each chloroplast has an outer and an inner membrane, which together regulate the movement of materials into and out of the organelle. Inside these membranes is a fluid matrix called **stroma** and a highly complex inner thylakoid membrane system. Figure 5.2.7 shows that the thylakoid membranes fold to form flat hollow discs, which form stacks called grana. Each **granum** looks like a stack of coins. Between the grana are flat membrane sheets called **thylakoid lamellae** (singular lamella).

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Chloroplasts and photosynthesis are examined in detail in Chapter 3.

A useful means of studying gas exchange and transport is by investigating factors that affect the rate of transpiration and the rate of photosynthesis. Simple experiments can be conducted in the laboratory or by using a virtual model. Scientists can use suspensions of isolated chloroplasts or green algae to test the effect of varying different factors on the rate of photosynthesis under controlled conditions.

BIOFILE ICT

Viewing chloroplast structures

The first definitive description of a chloroplast was given by Hugo von Mohl in 1837. He described these structures as discrete bodies within the green plant cell. Viewing chloroplasts under a microscope today allows us to recognise the internal structures. Comparing an electron micrograph image of a chloroplast with a diagrammatic representation is a useful way to link the various structures of the chloroplast with a function (Figure 5.2.7).

Electron micrographs of a chloroplast may differ in appearance depending on where the cross-section of the chloroplast falls.

Typically, chloroplast diagrams should display the following features:

- usually cylindrical in appearance with a double membrane, which regulates the movement of materials
- flattened discs (thylakoids) arranged into stacks (grana) to increase the surface-area-to-volume ratio
- starch granules may be visible as dark spots; they store the sugars produced in photosynthesis
- chloroplast ribosomes and DNA are usually not visible at standard resolutions and magnifications.

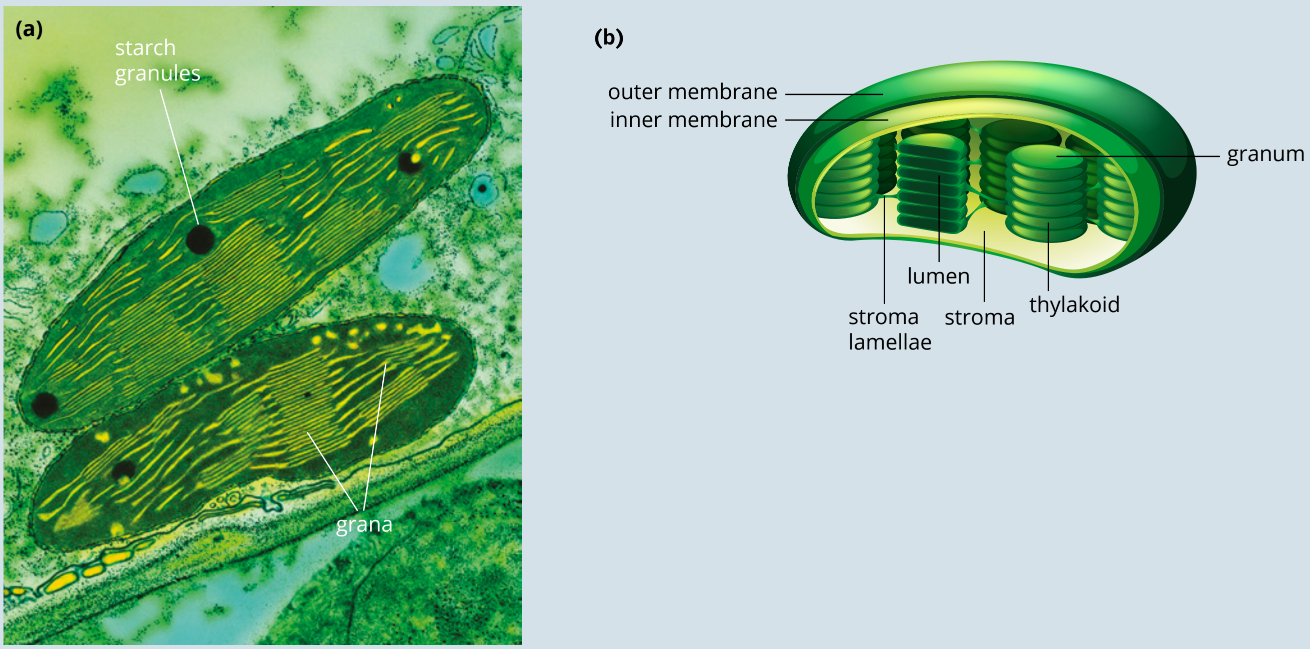

FIGURE 5.2.7 (a) A transmission electron microscope (TEM) image of two chloroplasts in the leaf of a pea plant (*Pisum sativum*). Each chloroplast is cut lengthways and contains stacks of flattened membranes (yellow) known as grana. The chloroplasts contain chlorophyll and are surrounded by an external double membrane. (b) A diagrammatic representation of a chloroplast

PHOTOSYNTHESIS INPUTS: CARBON DIOXIDE, WATER AND LIGHT ENERGY

Photosynthesis is essential for autotrophs to fulfill their nutrient and gas requirements. If we look closely at the process of photosynthesis, we can predict that the rate at which it occurs will be affected by several factors. The main requirements of photosynthesis are carbon dioxide, water and light energy. If any one of these factors is in limited supply, it is reasonable to predict that the rate of photosynthesis will also be limited. The biochemical process of photosynthesis is covered in Chapter 3 and is reviewed here in the context of the nutrient and gas requirements of autotrophs.

Terrestrial plants receive their carbon dioxide from the air. Aquatic plants can use the carbon dioxide dissolved in water.

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Photosynthesis can be represented as a word equation or a chemical equation.

Word equation: water + carbon dioxide → glucose + oxygen

Chemical equation:
$6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$

FIGURE 5.2.9 This plant has wilted due to water loss. When water is not available, the plant cells lose water, reducing the turgor (pressure) inside the cell. When turgor is reduced, the cells cannot maintain a rigid shape, and the plant collapses.

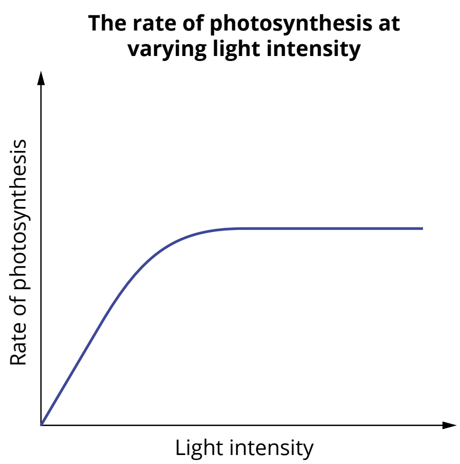

FIGURE 5.2.10 Light saturation curve. At a constant temperature and with unlimited carbon dioxide, the rate of photosynthesis will increase as the light intensity increases up to the point at which the photosynthetic processes are working at a maximum rate.

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Carbon dioxide

The carbon dioxide level in the air remains relatively constant. Therefore, the factors that affect the amount of carbon dioxide available for photosynthesis in most terrestrial plants are the number of stomata in the leaves, and whether these stomata are open or closed. If the stomata are closed, photosynthesis will use up the carbon dioxide available, reducing the carbon dioxide concentration in the leaves. With less carbon dioxide available, the rate of photosynthesis will be limited, even in the presence of light.

In the laboratory, it is possible to control the concentration of carbon dioxide to which plants are exposed without changing other factors. Figure 5.2.8 compares the rate of photosynthesis for a plant exposed to different concentrations of carbon dioxide at different light intensities.

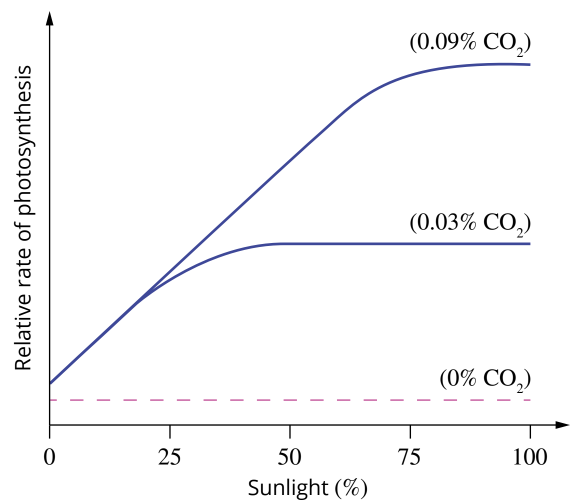

FIGURE 5.2.8 The rate of photosynthesis increases with increasing light intensity at two different concentrations of carbon dioxide. At 0.03% carbon dioxide, the rate of photosynthesis increases until approximately 40% sunlight, at which point the rate of photosynthesis is limited by the availability of carbon dioxide. At 0.09% carbon dioxide, the rate of photosynthesis continues to increase up to approximately 75% sunlight. The concentration of carbon dioxide in the atmosphere is currently about 0.04%.

Water

Because the amount of water used in photosynthesis is small compared with the amount needed to keep the cells alive, a living plant cell will normally have sufficient water for photosynthesis to occur. When water availability is low and a plant is suffering from water stress (Figure 5.2.9), the stomata in the leaf close to conserve water. This limits the amount of carbon dioxide that can enter the leaves for photosynthesis.

Water is essential for all life forms. In plants, water molecules are split to form oxygen gas and hydrogen ions. Plants harness the energy involved in the process of water splitting to drive photosynthesis. The hydrogen ions go on to produce **adenosine triphosphate (ATP)**, and can also combine with carbon to produce glucose. Water is also an output of photosynthesis. You will learn in Chapter 6 that water is transported in the **xylem** of vascular plants from roots to leaves, where photosynthesis takes place.

Light energy

In the laboratory, chloroplasts can be extracted from plant cells and tested in isolation. By varying the amount of light shining on isolated chloroplasts while keeping the carbon dioxide levels constant, it is possible to measure the rate at which photosynthesis occurs at different light levels. The results of this experiment are shown in Figure 5.2.10, and present what is known as a light saturation curve.

The curve shows a steady increase in the photosynthesis rate with an increase in light intensity until a plateau is reached. The plateau indicates that there is a maximum rate at which photosynthesis can occur. Assuming unlimited amounts of carbon dioxide (and water), the limit will be the point at which all the photosynthesis systems and enzymes in the chloroplasts are working at their optimum rate.

In the natural environment, the amount of light available for photosynthesis will be determined by the amount of sunlight. Trees and taller plants shade plants on the forest floor, while the amount of light available to aquatic plants depends on how far underwater they grow (Figure 5.2.11). Sunlight will also vary during the cycle of a day and will change with the seasons and the weather.

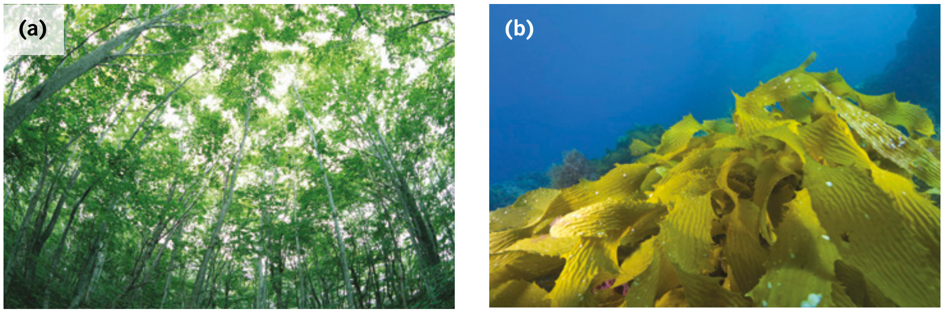

FIGURE 5.2.11 (a) Plants growing on the forest floor will receive less light than taller trees. (b) Some aquatic photosynthetic organisms, such as this sea kelp, can only grow near the water's surface. As the water depth increases, less light is available.

When the temperature is below the optimum range of an enzyme, there is low kinetic energy (movement) in the molecules. Therefore, the rate of photosynthesis falls in low temperatures, because enzyme activity is low and the water and carbon dioxide molecules are moving more slowly. The enzymes of plants from cold climates have a lower optimum temperature range than enzymes of tropical plants.

PHOTOSYNTHESIS OUTPUTS: OXYGEN AND GLUCOSE

Oxygen

Oxygen is a product of photosynthesis and is often used as a measure of photosynthetic rate. The greater the amount of oxygen produced by a plant, the greater its rate of photosynthesis. In the laboratory, it is possible to measure the amount of oxygen produced by a plant and therefore infer its rate of photosynthesis. This experiment can be conducted under different environmental conditions to understand the environmental factors required for optimal rates of photosynthesis. The oxygen output of a plant is influenced by both the amount of oxygen produced by photosynthesis and the amount used by cellular respiration in the plant's cells.

Glucose

It is possible to directly measure the rate of **mineral** uptake in a plant by measuring the amount of glucose the plant produces, but this can be difficult to do.

An alternative, indirect way to measure glucose production is by measuring biomass. Biomass is the weight of organic matter derived from living, or recently living, organisms. To measure glucose production in this way, the plant tissue must be completely dehydrated before weighing to ensure the change in biomass represents only organic matter, and not water. The amount of glucose in a plant can also be indirectly estimated by measuring **starch** levels, because glucose is stored as starch. An iodine-staining technique turns starch purple and is a useful qualitative measure. A colorimeter can then be used to obtain a quantitative result.

BIOFILE S

The impact of rising carbon dioxide levels on food crops

Rising atmospheric carbon dioxide levels and consequent global warming will increase the rates of photosynthesis in plants. This means plants will produce more glucose, and it has long been predicted that crops will grow more quickly as a result. However, scientists studying the effects of elevated carbon dioxide levels on some important food plants have made some unexpected and alarming findings (Figure 5.2.12).

In experiments in which crops were grown in an atmosphere with artificially elevated carbon dioxide levels, overall plant growth increased, but levels of zinc, iron and protein in the plants fell. People rely on food from crops for these important nutrients, and their lack may lead to serious malnutrition for people throughout the world.

FIGURE 5.2.12 The nutritional value of important food crops, such as wheat, may be reduced with rising atmospheric carbon dioxide levels.

BIOLOGY IN ACTION CCT ICT S

The Global Artificial Photosynthesis Project

The Global Artificial Photosynthesis Project (GAP Project) is an international venture that aims to develop more effective technologies for harvesting solar energy by copying the natural process of photosynthesis. Due to expanding global populations, large-scale long-term energy and food production options are likely to be needed in the future. New technologies that collect and store sunlight in the form of chemical potential energy offer great promise in this area.

The GAP project is one possible future option. It uses nanotechnology-based chromophores to harvest light energy and convert it to electrons. Once the energy is in the form of electrons, a redox reaction is used to generate chemical fuel sources, such as methanol, which is carbon neutral and renewable (Figure 5.2.13).

To produce the methanol fuel, nanotubes are seeded with cobalt oxide crystals and embedded within a silica membrane. The cobalt oxide crystals are a photocatalyst, which uses the energy in sunlight to split water molecules. This frees up electrons and oxygen, which then reacts with carbon dioxide to produce methanol. This form of artificial photosynthesis is intended to produce clean energy, with only heat released as a by-product. If applied correctly, there are many potential benefits to such a project. Artificial photosynthesis could help crop production on varying soil types, reduce atmospheric carbon dioxide levels and reduce the demand for fossil fuels.

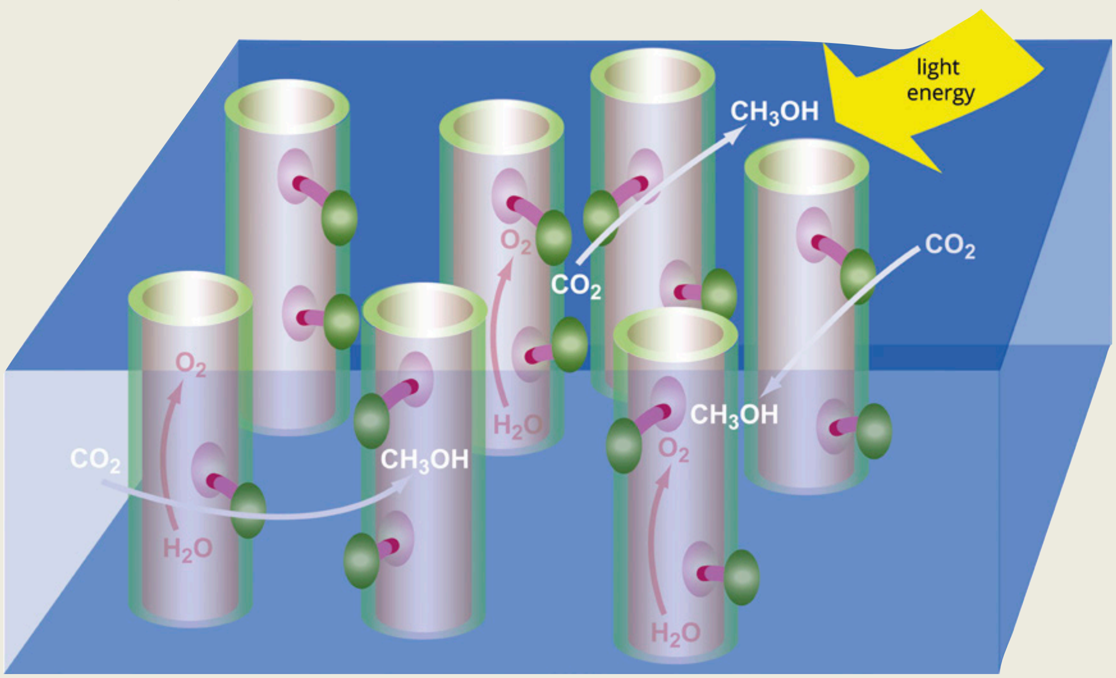

FIGURE 5.2.13 Nano-scale artificial photosynthesis could produce methanol (CH_3OH), a carbon-neutral and renewable fuel. Nanotubes (grey) are seeded with cobalt oxide crystals and embedded within a silica membrane (blue). The cobalt oxide crystals use light energy from sunlight (yellow arrow) to split water (H_2O) molecules, freeing up electrons and oxygen (O_2). The oxygen then reacts with carbon dioxide to produce methanol.

VASCULAR PLANTS

Vascular plants include ferns, cycads, conifers and flowering plants. They usually grow in terrestrial environments, and are characterised by the presence of vascular tissue, which is specialised for transporting fluids. Vascular tissue will be discussed in detail in Chapter 6, but includes:

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- xylem—transports water and inorganic nutrients (mineral ions) absorbed from the soil up the plant
- **phloem**—transports dissolved sugars produced by photosynthesis from the leaves throughout the plant, and organic substances such as **amino acids**.

Plant tissue is also organised into organs. Two of the major organs in plants are leaves and roots (Figures 5.2.14 and 5.2.15). In vascular plants, vascular tissue is found within both these organs.

Roots

The root tissue of plants is usually located in the soil and is not visible without extracting a plant from its soil bed (Figure 5.2.14). On close inspection of a root system, the fine detail and intricate structure of the tissue is clear. Roots have a critical role in anchoring a plant to the soil, as well as absorbing water and dissolved minerals from the soil for growth and photosynthesis. Roots also store glucose produced by the plant.

Roots have structural adaptations that help them absorb water. Examination of the anatomy of a root reveals highly specialised cells. The exterior of the root is the epidermis, composed of epidermal cells. Some of these epidermal cells have long, fine extensions called root hairs, which increase surface area and maximise water and mineral uptake. The next layer of a root is the cortex. The cortex is composed of parenchyma cells, which can store nutrients and starch. The innermost central region of the root contains the vascular tissue: xylem and phloem.

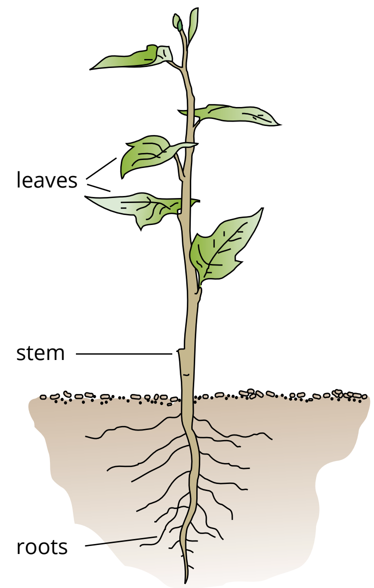


FIGURE 5.2.14 The basic structure of a vascular plant: leaves (for photosynthesis), stem (for support) and roots (for water absorption and to anchor the plant into soil)

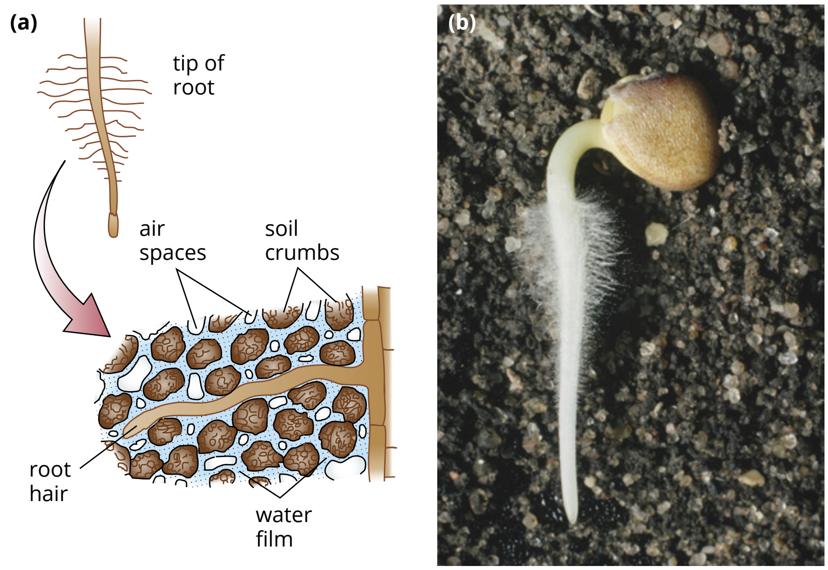


FIGURE 5.2.15 (a) Water and inorganic nutrients are absorbed by the roots from the soil through many fine root hairs. (b) Root hairs on a radish seedling. The branched structure of the fine root hairs provides a greater surface area for the seedling to absorb water.

> The epidermis is the outer layer of cells that cover the leaves, stems and roots of a plant, forming a protective barrier.

> The cortex is a layer of the stem and roots of a plant bounded by the epidermis and inner endodermis.

Leaves

In vascular plants, a leaf is an organ composed of three distinct layers of specialised cells, or tissues (Figure 5.2.16):

- upper epidermis
- mesophyll
- lower epidermis.

The epidermis is a layer of cells covering the entire leaf. It secretes a waterproof waxy layer called the cuticle. Together the epidermis and cuticle provide a barrier that protects the cells and tissues inside the leaf and prevents excess water loss. The epidermal cells lack chloroplasts, but are transparent, allowing sunlight to reach the photosynthetic cells below. Within the lower epidermis are the stomata. The stomata regulate the exchange of carbon dioxide, oxygen and water vapour between a plant's internal and external environment.

Between the epidermal layers are the mesophyll cells, where photosynthesis takes place. The cells closest to the upper epidermis are the **palisade mesophyll** cells. These cells contain many chloroplasts and are tightly packed together. The **spongy mesophyll** cells below the palisade mesophyll cells are loosely packed together, with air spaces between them to allow gas exchange. These cells contain fewer chloroplasts.

The vascular tissue (xylem and phloem) is also located between the two layers of epidermal cells. Vascular tissue is often visible in leaves as veins.

Table 5.2.1 summarises the structure and function of leaf parts.

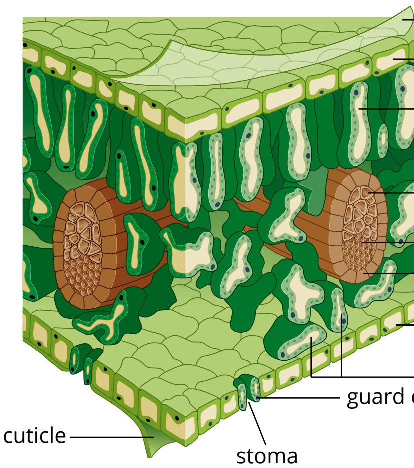


FIGURE 5.2.16 The three distinct layers of cells in leaves are the upper epidermis, the mesophyll and the lower epidermis.

TABLE 5.2.1 Leaf tissue structure and function

Leaf tissue	Structure	Function
cuticle	thin, waxy waterproof layer	protects the inner cells, prevents water loss and allows sunlight to penetrate for photosynthesis
epidermis (upper and lower)	transparent and usually thin	protects the inner cells, prevents water loss and allows sunlight to penetrate for photosynthesis
epidermis and cuticle	contains guard cells surrounding stomata	regulates gas exchange and water loss—the waxy cuticle protects the leaf from excess water loss and the opening and closing of the stomata controls the amount of gas and water vapour entering and exiting the leaf
mesophyll	palisade mesophyll: tightly packed column-shaped cells with many chloroplasts, close to upper epidermis	photosynthesis
	spongy mesophyll: loosely packed, rounded cells with fewer chloroplasts, with air spaces around the cells	gas exchange, including the diffusion of carbon dioxide throughout the leaf
xylem and phloem	tubular vessels	transport fluids

Pith is tissue located in the stems of vascular plants. It is composed of spongy parenchyma cells, which store and transport nutrients.

Cambium is plant tissue located between the xylem and the phloem in stems and roots of vascular plants. It is composed of undifferentiated cells that divide during growth to form vascular tissue.

SKILLBUILDER CCT

Microscope images of plant root, stem and leaf tissue

Viewing plant tissue under a light microscope is a useful way to recognise different structures that lie within the vascular tissue of a plant. By observing a transverse section of different parts of a plant (leaf, stem and root), it is possible to recognise the position of the major vascular tissues (xylem and phloem).

The arrangement of xylem and phloem tissues in roots, stems and leaves is distinctive. Roots have a central core of xylem in a star or cross shape, with phloem between the arms of the xylem. In stems and leaves, the xylem and phloem are grouped into vascular bundles, as shown in Figure 5.2.17. These vascular bundles extend into the leaves and are visible as veins. Other plant tissues include the cortex, epidermis, pith and cambium. The distribution of tissue types differs between plants according to their functional requirements.

Using light microscopy allows you to view living cells in colour. Figures 5.2.17, 5.2.18 and 5.2.19 highlight some of the main cell and tissue types within the leaf, stem and roots of a plant.

Preparation time for preparing a microscope slide is usually quick, and coloured stains can highlight different cell components. Since most biological structures are transparent, it is helpful to use a stain to give contrast between different structures.

A wide variety of stains can be used in microscopy. Stains such as methylene blue in low concentrations do not harm tissue, and so can be safely used on living materials. Stains that are used on living material are called vital stains.

Common stains for temporary slides include:

- iodine—stains carbohydrates in plant and animal specimens brown to black
- methylene blue—stains acidic cell parts, such as the nucleus, blue
- safranin—stains chromosomes in plant tissue red
- eosin Y—stains alkaline cell parts, such as the cytoplasm, pink.

After preparing, mounting and staining a specimen of plant tissue, the glass slide is placed on the stage of a light microscope, under the lenses. Light travels through the specimen and into the lens system, and the image is viewed by eye or with a digital camera. The objective lens can be adjusted to view each specimen under different magnifications according to the size of the structures to be viewed.

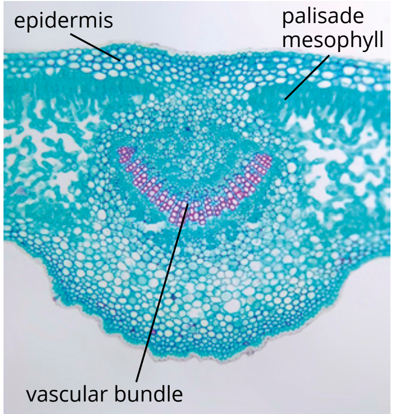


FIGURE 5.2.18 This microscopic cross-section of a typical leaf shows the epidermis, palisade mesophyll and vascular bundle (containing the xylem and phloem).

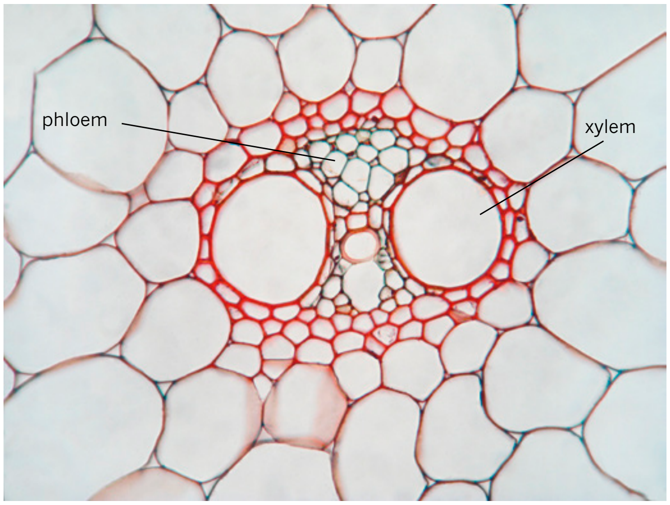


FIGURE 5.2.17 A cross-section through a stem, showing a vascular bundle containing xylem and phloem

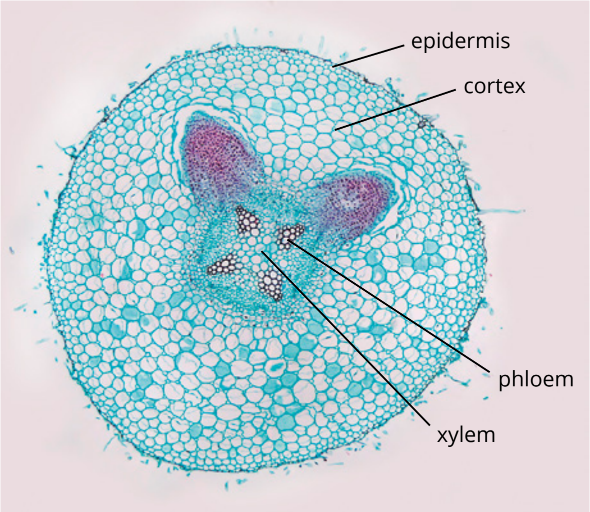


FIGURE 5.2.19 This microscopic cross-section of a root from a soy bean plant shows the epidermis, cortex region and vascular bundle (containing the xylem and phloem).

5.2 Review

SUMMARY

- Gas exchange in plants occurs through a structure called the stoma (plural stomata). The stoma is the opening to a stomatal cell, which is located in the lower epidermis of a leaf.
- Chloroplasts are the site of photosynthesis in the leaves and green stems of plants.
- Chloroplasts contain thylakoid membranes and fluid called stroma. They also contain their own DNA and ribosomes.
- Photosynthesis is essential for autotrophs to fulfill their nutrient and gas requirements.
- The rate of photosynthesis in a plant can be affected by:
  - inputs—carbon dioxide, water and light energy
  - outputs—oxygen and glucose.
- Plants have an optimum temperature range for photosynthesis. If it is too cold, the rate of reaction will be slow; if it is too hot, the enzymes in the chloroplast can denature.
- The vascular tissues are:
  - xylem, which carries water and mineral ions from roots to leaves
  - phloem, which carries sugars and other organic molecules from leaves to roots.

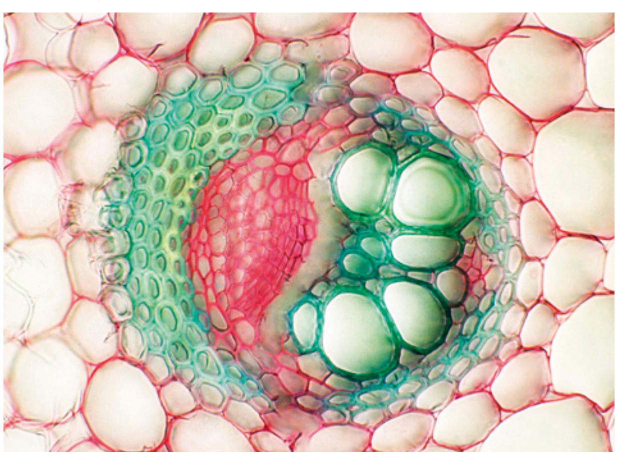
KEY QUESTIONS

1 When a plant closes its stomata, it can no longer exchange oxygen and carbon dioxide, therefore the rate of photosynthesis decreases. What is the benefit of closing the stomata?

2 **a** Describe the terms 'turgid' and 'flaccid'.
b Explain how the movement of potassium ions in a guard cell can result in the cell becoming turgid.

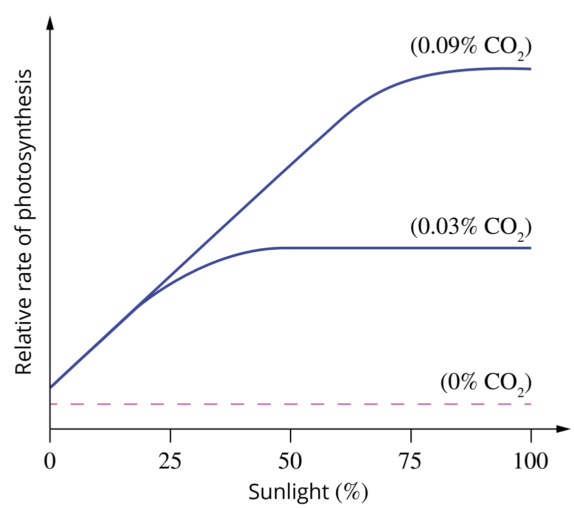
3 Draw a labelled diagram comparing the structure of a chloroplast viewed under a light microscope and a diagrammatic representation of a chloroplast.

4 The following image is a transverse section through a buttercup stem. Label the phloem and xylem tissue on this image.



5 Looking at the graph below, what is the overall effect of increased carbon dioxide levels on the rate of photosynthesis?

The effect of carbon dioxide concentration on the rate of photosynthesis at varying light intensity



6 If a plant is given unlimited carbon dioxide and unlimited access to light, will the rate of photosynthesis increase? Explain your answer.

5.3 Obtaining nutrients: heterotroph digestive systems

Mammals are heterotrophs; unlike plants, they cannot make organic molecules from inorganic materials. Therefore, they must consume other organisms or their products to obtain organic molecules. As well as needing organic molecules to provide chemical energy, heterotrophs require other organic molecules, such as vitamins, amino acids and fatty acids. Their diet must also contain minerals and water. Chapter 3 examines cell requirements in more detail.

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NUTRITIONAL REQUIREMENTS OF HETEROTROPHS

Carbohydrates and lipids

Carbohydrates are an important source of immediate energy for all living organisms. The monosaccharide glucose is broken down to produce ATP during cellular respiration. Animals store carbohydrates in the form of the polysaccharide glycogen.

Lipids are also an important energy store in animals, and they are required for cell membranes, hormones and vitamins.

Amino acids

Amino acids are required for protein synthesis. Animals cannot make all the amino acids they need, but can change some amino acids into others. However, nine amino acids cannot be made in this way (Table 5.3.1). These are called the **essential amino acids**, because they must be included in the diet. Because amino acids are not stored, all required amino acids must be present in the blood for protein synthesis to proceed smoothly. This means that all essential amino acids should be eaten regularly to maintain their levels in the blood.

All nine essential amino acids are found in milk, eggs and meat. Wheat, corn, rice and other grains contain very little lysine. Beans, lentils and other legumes are rich in lysine but contain little methionine, so it is good to eat grains and beans together. Other sources with moderate to high amounts of amino acids are shown in Table 5.3.1.

TABLE 5.3.1 The nine essential amino acids

Amino acid	Main sources
isoleucine	fish, cheese, seeds and nuts, lentils, milk, eggs
leucine	grains, cereals, nuts, soybeans, lentils and beans, corn, milk, eggs, chicken, fish
lysine	fish, potatoes, lentils and beans, milk, eggs
methionine	fish, soybeans, cottage cheese, yoghurt, pumpkin seeds, sesame seeds, milk, eggs
phenylalanine	cheese, wheat germ, oats, milk, eggs, red meat
threonine	wheat germ, many nuts, beans and seeds, milk, eggs, spinach, turkey
tryptophan	pineapple, yoghurt, bananas, unripened cheese, milk, eggs, turkey
valine	soy flour, brown rice, cottage cheese, fish, seeds and nuts, lentils, mushrooms, milk, eggs, turkey
histidine	red meat, chicken, fish, dairy products, eggs, kidney beans (infants cannot synthesise histidine, so they must obtain it from their diet)

Vitamins and minerals

Vitamins are a diverse group of organic compounds made by plants and by some simple animals and microorganisms. They are not used to supply energy, but are required in very small amounts for cellular processes. Many vitamins are important because they are needed to make certain enzymes.

Mammals need 13 vitamins. Like most animals, they must obtain vitamins from their diet. Some vitamins that are important for human health are listed in Table 5.3.2.

Minerals are also essential for cellular processes. Dietary minerals are chemical elements that are required as essential nutrients by an organism. Minerals are a major constituent of structures such as teeth and bones, and can be important components of body fluids. A deficiency in one or more dietary mineral can result in a disorder, such as lack of calcium impacting on bone mineralisation.

TABLE 5.3.2 The roles of some important vitamins in the human body

Vitamin	Role in the human body
vitamin A	needed for vision, healthy skin, bones and teeth
vitamin B1 (thiamine)	a coenzyme needed for the metabolism of energy in the body; needed for nerve functioning
vitamin B12	supports the enzyme needed for making new cells
vitamin C	needed for growth and repair of tissues (e.g. healing wounds)
vitamin D	needed for absorption of calcium
vitamin E	protects cells from damage by free radicals
vitamin K	needed for blood clotting and building strong bones

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Naming vitamins

Vitamins were named alphabetically (i.e. A, B, C) before their chemical structure was understood. This way of naming them is still used, although we now know their chemical formulae and dietary sources. We also know a great deal about their functions in the body.

Vitamins A, D, E and K are fat soluble, and are therefore obtained from food containing fats and oils. The remaining nine vitamins (the B group and vitamin C) are water soluble. Fat-soluble vitamins are stored in the liver, whereas excess water-soluble vitamins are excreted. This is why we need to regularly eat food containing vitamins B and C. Vitamin C is used up in the reaction in which it is involved, whereas the other water-soluble vitamins are recycled as they function. Therefore, the daily requirement for vitamin C is relatively large.

More than 20 minerals are also required in our diet. The main minerals required are calcium, phosphorus, magnesium, iron, sodium, potassium and iodine. Others are needed only in trace (small) amounts. Mineral ions occur in the cytosol of cells, in structural components (e.g. bone) and in the molecules of many enzymes and vitamins.

A vitamin deficiency can be caused by an inadequate diet or poor absorption from the gut. Pernicious anaemia, for example, is a disease due to a vitamin deficiency. It is caused by the lack of a substance in the gastric juices that is needed for the absorption of vitamin B12 from the intestine. In this case, increasing the intake of vitamin supplements is not likely to remedy the problem.

In normal circumstances, a healthy person eating a balanced diet should not require additional vitamin or mineral supplements (Table 5.3.3). An excessive intake of water-soluble vitamins should cause no direct harm, because they are excreted rapidly in urine. An excessive intake of fat-soluble vitamins can be dangerous, because they are not excreted and are retained in the body. Even a fivefold excess may cause disease symptoms.

TABLE 5.3.3 Some estimated average daily nutritional requirements of humans. The recommended daily intakes are higher than these values.

	Age	Protein (g)	Calcium (mg)	Iron (mg)	Thiamine (mg)	Niacin (mg)	Vitamin C (mg)
Females	14–18	45	1300	15	1.1	14	40
Females	19–50	46	1000	18	1.1	14	45
Males	14–18	65	1300	11	1.2	16	40
Males	19–50	64	1000	8	1.2	16	45
Pregnant females (trimesters 2 and 3)	19–50	60	1000	27	1.4	18	60
Lactating females	19–50	67	1000	9	1.4	17	85

FOOD MUST BE DIGESTED

Organisms are composed of many different types of complex organic molecules. When eaten as food, these molecules are too large to be simply absorbed into an animal's body.

The principle function of the digestive system of any animal is the **digestion** and absorption of food. In other words, the digestive system breaks down organic food into molecules small enough to be able to pass through cell membranes and into cells for use in the production of energy.

Before food passes into the digestive system of a mammal, it is physically broken into pieces by the teeth. Mucus is secreted to protect the lining of the gut and to lubricate food for easier passage. The food then moves along the gut past a series of **digestive enzymes** that sequentially break down the various compounds for absorption. **Proteins** are broken down to amino acids. Fats and lipids are broken down to fatty acids. And **glycerol** and complex carbohydrates such as starch are broken down to simple sugars.

The food you eat does not become part of your body until it has been absorbed by the cells lining the walls of your intestine. The digested food then passes into the bloodstream and is carried throughout the body. If food is not absorbed, it continues through the intestine and is passed out again as faeces (**egestion**).

Digestion is the breakdown of food into a form that can be used by an organism for metabolism. This involves physical and chemical breakdown.

Do not confuse egestion with **excretion**. Excretion refers to the removal of substances that were once part of the body, and occurs largely in the kidneys. Excretion is covered in more detail in Section 3.3.

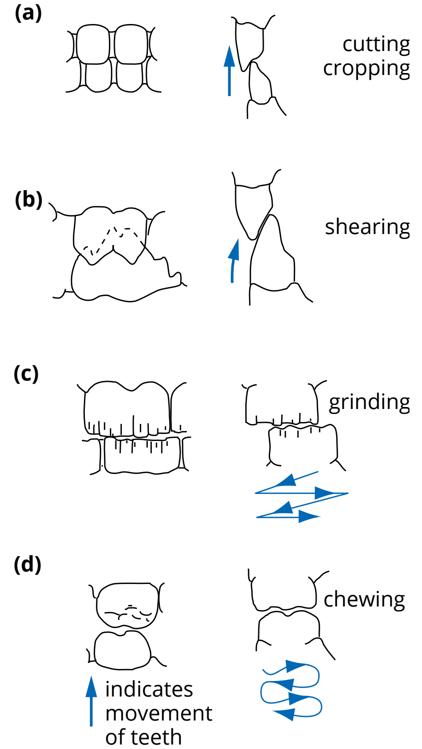

FIGURE 5.3.1 In mammals, the tooth structure is adapted for the mechanical breakdown of different types of foods. (a) Incisors are typically used for cutting and tearing. (b) Carnivores have large, powerful molars that shear through tough sinews and bones. (c) Herbivores have molars that grind fibrous plant foods. (d) Omnivores, such as humans, have molars that roll and crush a variety of foods.

Physical digestion

Digestive enzymes can only act on the outside surface of food. If food is swallowed in large pieces, the enzymes have a relatively small surface area to work on. Unless the digestive system is extraordinarily long, most of the food would remain undigested. Given the relationship between surface area and volume, digestion is much faster if food is in small pieces and the enzymes have a proportionally larger area to act upon. You learnt about surface-area-to-volume ratio in Chapter 3.

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Therefore, it is important to have a mechanism for breaking down large food into pieces to increase its surface area. This process is called **physical digestion**. Animals have developed a variety of structures to break down food physically—for example, the teeth of **vertebrates**, which break food into pieces small enough to be swallowed (Figure 5.3.1). You will learn more about teeth as an adaptation to diet in Chapter 8.

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To improve the efficiency of digestion, this physical breakdown should take place before chemical digestion is completed. In contrast to chemical digestion, physical breakdown does not chemically change food molecules.

Bile is important in the physical breakdown of fats, but it is not an enzyme. Bile is a fluid produced by the **liver** and released into the **small intestine**, where it acts like a detergent to emulsify fats—breaking up large fatty masses into small droplets. This increases the surface area of fats available for digestion by enzymes.

Chemical digestion

The process of breaking apart complex molecules into simple molecules is called **chemical digestion**, and is carried out by the action of enzymes. Enzymes are important in digestion, because they greatly increase the rate of breakdown of food molecules.

Most digestive enzymes split food molecules by the process of **hydrolysis** (from Greek 'hydro', meaning 'water', and 'lysis', meaning 'split'). This means the enzymes split the food molecule by adding a molecule. There are three main types of digestive enzymes (Figure 5.3.2):

- **amylases**, which act on carbohydrates (e.g. starch)
- **proteases**, which act on proteins
- **lipases**, which act on lipids.

Digestive enzymes are often named according to the substance on which they act, with the common ending '–ase'. For example, protease digests proteins and lipase digests lipids.

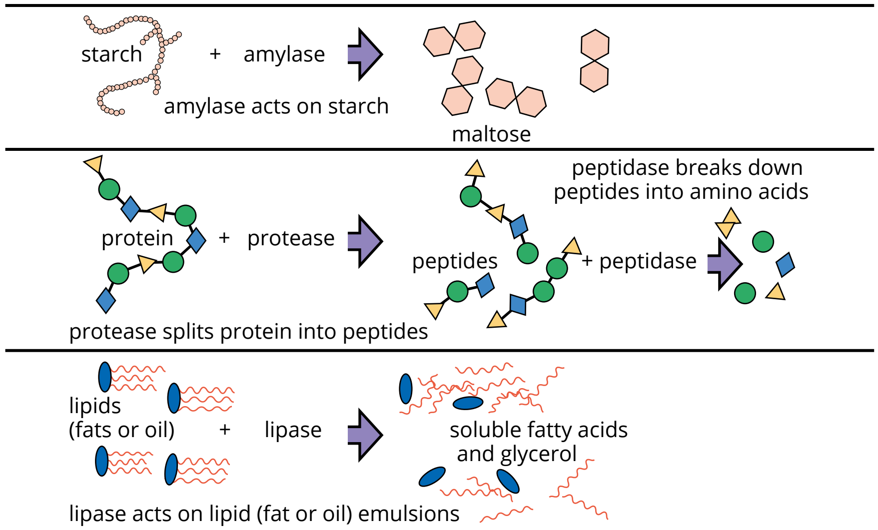

FIGURE 5.3.2 Digestion involves splitting of food molecules into components small enough to pass across cell membranes and into the body. Amylase breaks down carbohydrates (e.g. starch), protease breaks down proteins and lipase breaks down lipids.

Digestive enzymes are manufactured by specific cells in the gut wall, and by the **salivary glands** and the **pancreas**. Many very large food molecules can only be broken down by several enzymes acting one after the other. In this case, the different enzymes are produced at appropriate sites along the digestive system.

The importance of pH

Because enzymes are proteins, they are sensitive to changes in the pH of a solution (Figure 5.3.3). Altering the pH changes the shape of protein molecules, which in turn alters their chemical properties. The change in shape alters the way that an enzyme binds with the molecule upon which it acts. Enzymes, therefore, have certain pH ranges over which they operate best. Different regions of the gut have different pH values that are most suitable for enzymes found in that region.

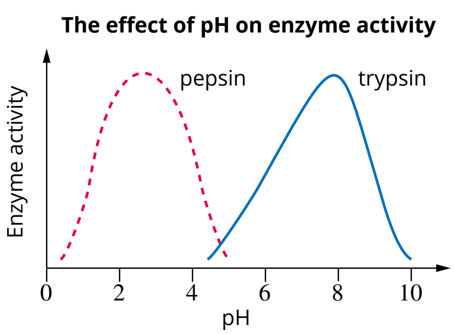

FIGURE 5.3.3 Pepsin and trypsin are both enzymes that digest proteins, but they have very different pH requirements. Pepsin is released in the stomach and is most active in its acidic environment. Trypsin is most active in the slightly alkaline small intestine.

Extracellular digestion

Chemical digestion can be extracellular or intracellular. **Extracellular digestion** occurs when, for example, cells release enzymes into the lumen (central cavity) of the small intestine. There, enzymes split the food molecules and the resulting smaller molecules are absorbed. A sea star turns its **stomach** inside out and releases enzymes directly onto the animal it has trapped. Carnivorous plants and fungi also release enzymes to break down their food before absorbing it. In each of these examples, digestion is extracellular, because it takes place outside cells. Sometimes, digestive enzymes are located on the actual surface of cells. As the food is digested into smaller molecules, the molecules pass immediately into the cells. Mammals and most other animals rely on some form of extracellular digestion.

In contrast, many protozoans and **invertebrate** animals, such as some species of mussels, sea jellies and free-living flatworms, use **intracellular digestion**. Their cells engulf small pieces of food into a membrane-bound **food vacuole** within the cell. Enzymes are released into the vacuole, the food is digested, and the resulting small molecules pass through the vacuole membrane and into the cell's cytosol.

FEATURES OF EFFECTIVE DIGESTIVE SYSTEMS

In one sense, the digestive systems of all animals must be effective, otherwise the animal would not survive. The digestive system of each animal must adequately meet their nutritional requirements to maintain normal functions at the cell, tissue, organ and system level.

Large animals require higher levels of energy and nutrients for their normal activities. Because mammals are **endothermic** (animals that maintain a stable body temperature, usually higher than their environment), they require a lot of energy to maintain their body temperature. They therefore need digestive systems that can efficiently extract large amounts of energy and nutrients from food resources. Characteristics of highly efficient digestive systems include:

- effective mechanisms for capture and handling of food
- appropriate physical breakdown of food
- a one-way gut with separation of tasks along its length
- efficient transport and storage of ingested food
- efficient sequential release of digestive enzymes
- an adequate surface area for maximum absorption of nutrients and water
- efficient egestion of unwanted materials.

DIGESTIVE SYSTEMS OF MAMMALS

All mammals need food and water, but different species have different food requirements, feeding behaviours and digestive systems. For example, cows are slow-moving and spend much of the day eating grass and chewing. In contrast, dingoes are energetic and active, and may spend only 5 or 10 minutes each day eating food. Dingoes and cows have many other differences that relate to their eating habits. Their teeth are very different, and cows have much larger and more complex intestines than dingoes (Figure 5.3.4).

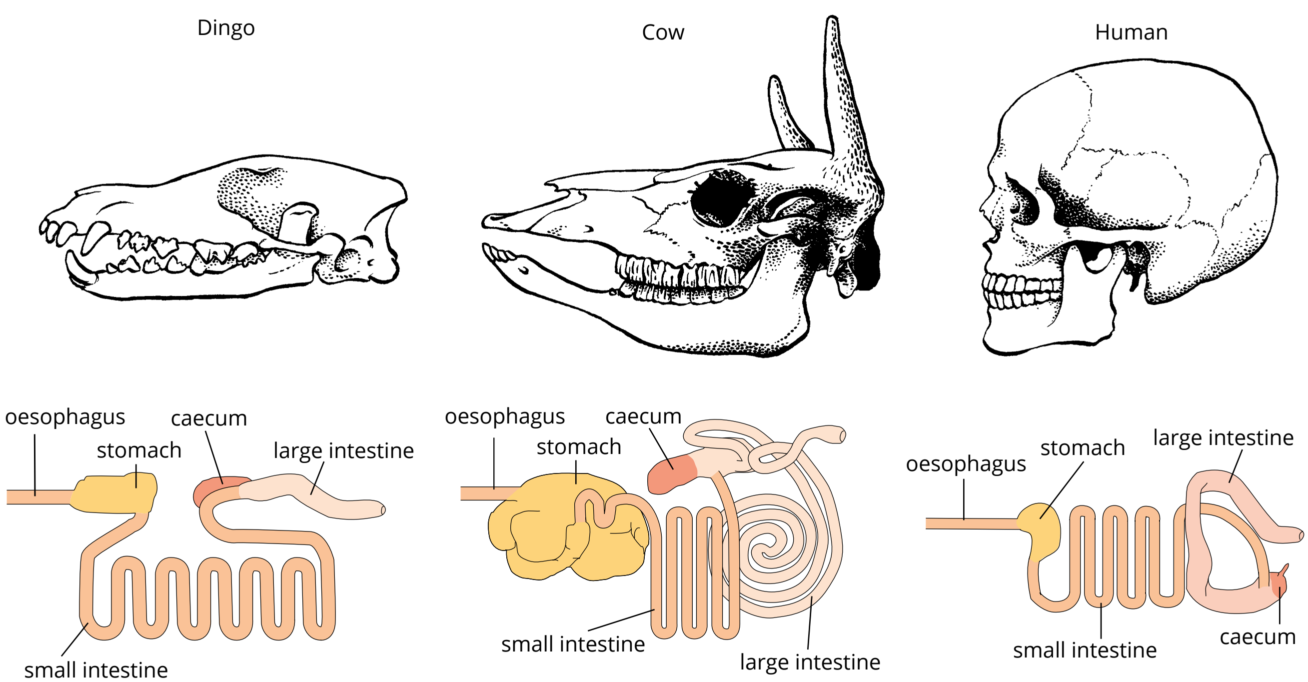

FIGURE 5.3.4 Skulls and digestive systems of a dingo (a carnivore), cow (a herbivore) and human (an omnivore). Scientists studying fossil jaws—or even a few fossil teeth—can predict the feeding behaviour and diet of a species, because teeth and jaws are adapted to suit the type of food that an animal eats.

The feeding behaviour, teeth and digestive system of a Tasmanian devil (*Sarcophilus harrisii*, Figure 5.3.5a) are similar to those of a dingo (*Canis lupus dingo*, Figure 5.3.4), while these features in a kangaroo (*Macropus* species, Figure 5.3.5b) are similar to those in a cow (*Bos taurus*, Figure 5.3.4). One common factor is diet: Tasmanian devils and dingoes eat meat, whereas kangaroos and cows eat plants. Dingoes, cows and humans are examples of animals with three different diets: carnivorous, herbivorous and omnivorous.

Carnivores

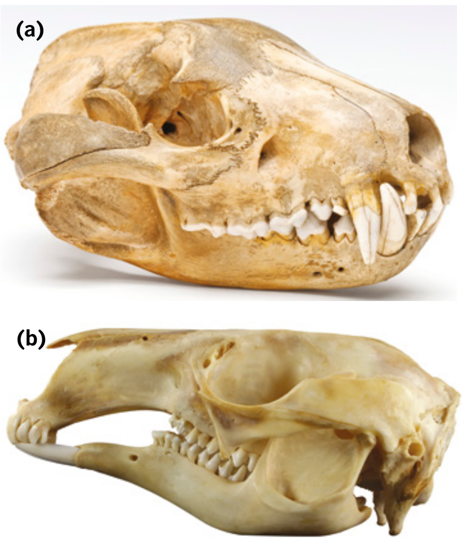

FIGURE 5.3.5 (a) The skull of a Tasmanian devil (*Sarcophilus harrisii*), a carnivore, and (b) the skull of a kangaroo (*Macropus* species), a herbivore

Animals that only eat meat are called carnivores, and include dingoes, cats and Tasmanian devils (Figure 5.3.5a). Carnivores have strong jaws for biting and their teeth are specialised for tearing meat. Many carnivores share adaptations, such as long, sharp canine teeth. Carnivores spend much less time eating than herbivores; some animals in the wild, such as lions, may not eat for days between meals.

Animal matter has a much higher proportion of extractable energy per gram than plant matter. Digestion of animal matter is therefore quicker and more efficient than digestion of plant matter. The digestive systems of carnivores are shorter and simpler than those of herbivores, and the carnivore digestive system produces all the enzymes needed for the complete digestion of meat. Carnivores do not have a large **caecum** (an enlarged pouch where the small and large intestines join) like herbivores do, because bacteria are not required to break down plant matter in their diet.

Herbivores

Animals that eat only plant material are called herbivores, and include cows, rabbits, kangaroos and koalas (Figure 5.3.5b). They need to consume a large amount of plant matter to meet their energy requirements. The tough **cellulose** cell walls of plants make plant matter much harder to break down and digest than animal matter. Herbivores typically spend much of the day eating, because the plant matter must be repeatedly ground by the teeth (physical digestion) to release the contents from broken cells and increase the surface area for enzyme action (chemical digestion). Herbivore teeth are usually flat for grinding and crushing hard plant matter. Herbivores also have specialised enzymes in their saliva to break down cellulose.

Because plant matter is more difficult to digest, herbivores require a longer digestive system than carnivores to increase the surface area over which nutrients can be absorbed. Microorganisms in the digestive tract of herbivores also play an important role in breaking down cellulose and providing essential nutrients to their animal hosts.

Herbivores use cellulose

Cellulose is the main component of plant cell walls, but its molecules are too large to be absorbed without digestion. Although many species of animals are herbivores, only a few can make the enzyme **cellulase**, which is needed to digest cellulose. To get around this problem, herbivores have a symbiotic partnership with bacteria that can produce cellulase. This type of partnership is called mutualism.

The cellulase-producing bacteria live in the gut of the animal, where they receive shelter and nutrients. In return, they convert cellulose into simpler molecules that can be absorbed by the gut. The bacteria also supply important vitamins, such as vitamin K and the vitamin B group.

The environment inside the gut is warm and wet, but has little or no oxygen. Therefore, the breakdown of cellulose must occur without oxygen by fermentation (using **anaerobic respiration**). Because of this, the part of the intestine in which the breakdown of cellulose occurs is sometimes called a fermentation chamber.

In herbivorous mammals, fermentation takes place in different parts of the intestine in different species, with varying degrees of efficiency. Generally, herbivorous mammals belong to either of two groups—hindgut or foregut fermenters.

Hindgut fermenters

In hindgut fermenters, fermentation occurs in either the caecum or the first part of the large intestine, as in the wombat (Figure 5.3.6a). In the koala, fermentation occurs in both the caecum and the first part of the large intestine (Figure 5.3.6b). Both regions are located after the small intestine, which is the part of the digestive tract where most absorption takes place. This arrangement limits the advantage obtained from this symbiotic relationship, because the products of their digestion are not completely absorbed.

Horses are hindgut fermenters. The relative inefficiency of their system can be seen by the large amounts of undigested plant material found in horse faeces. Some hindgut fermenters, such as possums and rabbits, overcome this problem by producing two types of faeces. One type comes directly from the caecum at night, and is eaten and reingested so that it can go through the intestine again. This practice is known as **coprophagy**, and allows the vitamins and products of fermentation to be absorbed in the small intestine.

Foregut fermenters

In foregut fermenters, such as the kangaroo (Figure 5.3.6c), the fermentation chamber is located before the stomach. In **ruminants**, such as cattle and sheep, it is called the **rumen**. Food can be regurgitated back into the **mouth** for further physical breakdown (rumination), and then returned to the rumen for continued chemical breakdown by bacteria. This regurgitated food is called cud.

Foregut fermentation has the obvious advantage that the products of digestion by microorganisms are available for absorption along the entire length of the small intestine. Kangaroos and wallabies are the only marsupial foregut fermenters.

Ruminant digestion has some drawbacks. The complete digestion of plant material in the rumen by microorganisms can take a long time—hours or even days—with constant regurgitation and chewing of the cud. If the quality of food is very low (that is, mostly cellulose and not much fresh, young plant growth) an animal may be starved of food that is digested enough for absorption, even though the animal has a very full rumen.

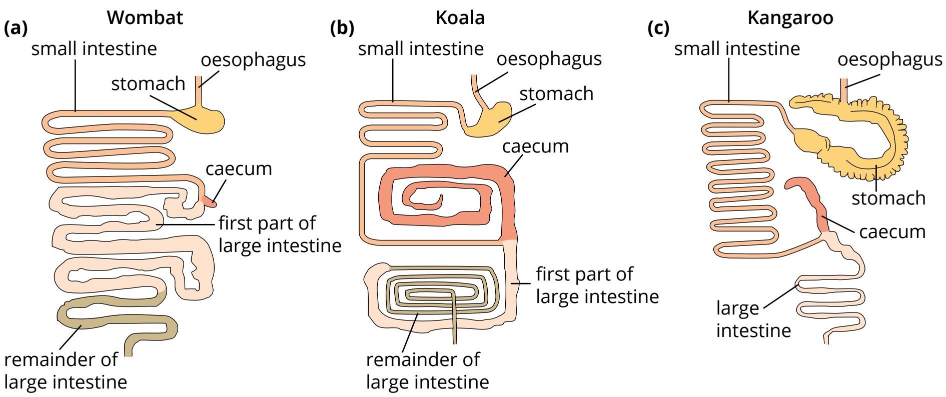

FIGURE 5.3.6 (a) Wombats, (b) koalas and (c) kangaroos are herbivores and use symbiotic bacteria for the digestion of cellulose. Wombats and koalas are hindgut fermenters, while kangaroos are foregut fermenters.

Omnivores

Animals that eat both plant and animal matter are called omnivores, and include humans, domestic dogs and pigs. The word omnivore is from the Latin 'omnivorus', which means 'all-devouring'. Omnivore digestive tracts can break down both meat and plant matter. The variety of different animals that are classified as omnivores can be further categorised based on their feeding behaviour and preferred foods. For example, animals that consume insects and plant matter are classified as insectivores.

Omnivores can consume a diverse range of foods, providing greater food security during periods of low food availability or environmental pressures.

Digestive system of humans

Because humans are omnivorous, our teeth are unlike those of carnivores or herbivores. We are not very good at chewing bones or grass—our preferred foods include both meat and plant material, and we often cook our food first.

Humans spend about 30 to 90 minutes each day eating, although the social aspects of eating may extend this time. The human digestive system is proportionally longer than that of a carnivore, but shorter than that of a herbivore.

The main regions of the human digestive system are the mouth and mouth cavity, **oesophagus**, stomach, small intestine, **large intestine**, **rectum** and **anus** (Figure 5.3.7). Glands and organs that assist with digestive functions are the salivary glands, pancreas and liver.

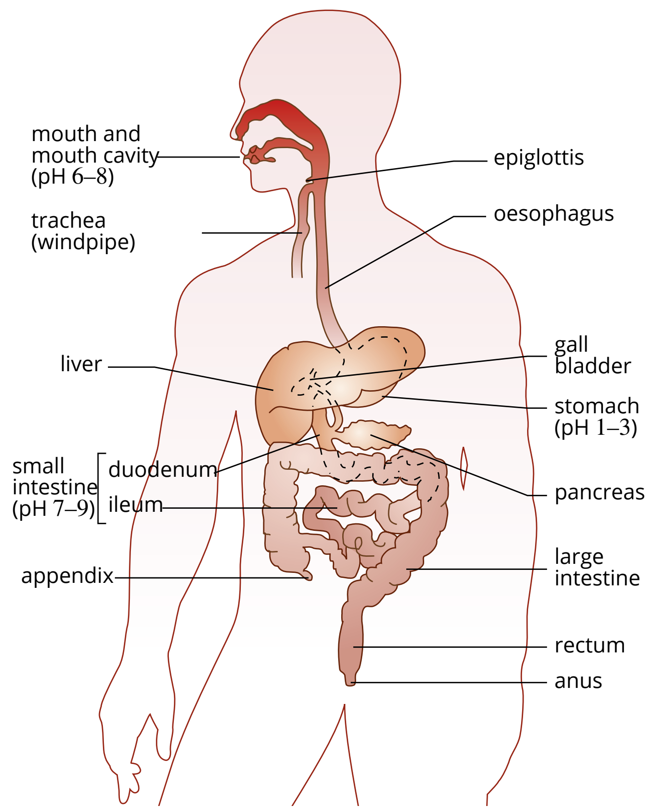

FIGURE 5.3.7 Components of the human digestive system

Key steps in the process of digestion in humans occur at the following sites:

- mouth
  - teeth mechanically break food into small pieces
  - saliva lubricates food and enzyme amylase digests starch into **maltose**
- **epiglottis** (a flap at the entrance to the **larynx**)
  - prevents food from entering the trachea and respiratory system, directing it down the oesophagus
  - is also associated with the gag and cough reflex
- oesophagus
  - a tube down which food travels to the stomach, aided by muscular contractions (**peristalsis**)
- stomach
  - secretes protein-digesting enzymes (proteases) and gastric juices to aid in food digestion
  - peristalsis of stomach muscles further breaks the food down and pushes it through the digestive system

- liver
  - has important roles in regulating **metabolism**, toxin removal and processing nutrients
  - stores excess glucose as glycogen (a polysaccharide or carbohydrate) for later conversion back to glucose when needed for energy
  - is the site of bile production for the breakdown of fats
- **gall bladder**
  - stores and concentrates bile before releasing it to the small intestine
- pancreas
  - produces digestive enzymes that are activated when the food reaches the duodenum (first part of the small intestine)
  - produces the hormones insulin and glucagon, which regulate sugar levels in the blood
  - produces sodium bicarbonate, which neutralises stomach acids in the food
- small intestine
  - absorbs nutrients and minerals from food
  - enzymes produced in the pancreas and the small intestine and bile from the liver and gall bladder further breakdown food products to facilitate nutrient and water absorption
  - has many blood vessels to absorb nutrients and waste products of digestion and deliver them to the circulatory system
- large intestine
  - absorbs water with soluble compounds, such as vitamins and minerals
  - undigested food leaves the body as faeces.

Structure of the small intestine

The principle organ of absorption is the small intestine. 'Small' refers to the diameter of this part of the intestine. The small intestine is long and has a large surface area, making it well suited for absorption. The internal surface area is further increased by millions of tiny folds called villi (singular **villus**), and by the presence of many **microvilli** on the exposed surface of the **epithelial cells** lining the **lumen** (Figures 5.3.8 and 5.3.9).

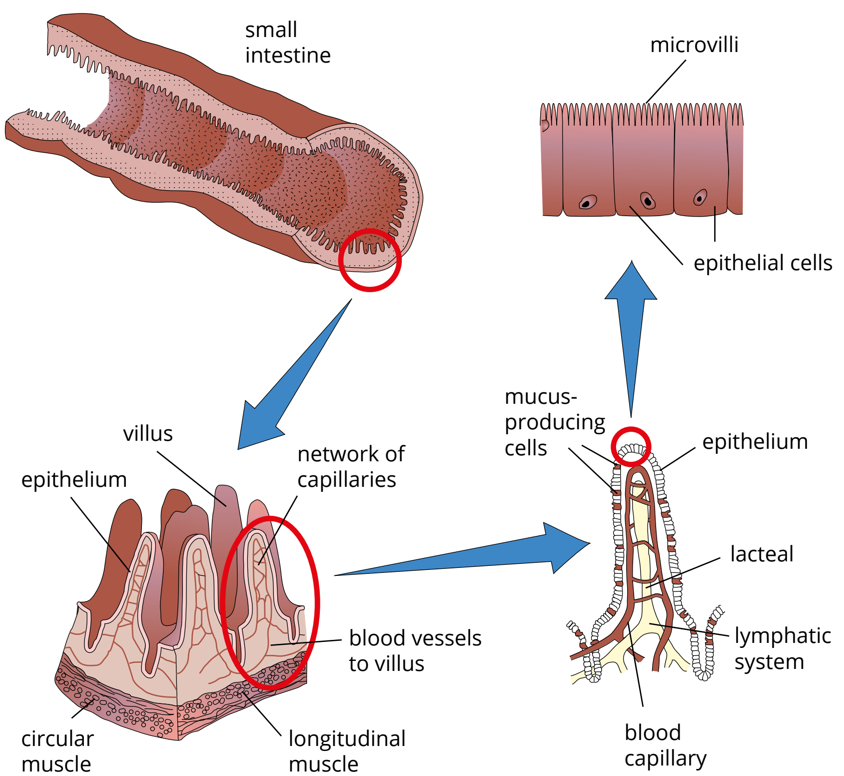

FIGURE 5.3.8 The internal surface of the human intestine, showing the villi and microvilli

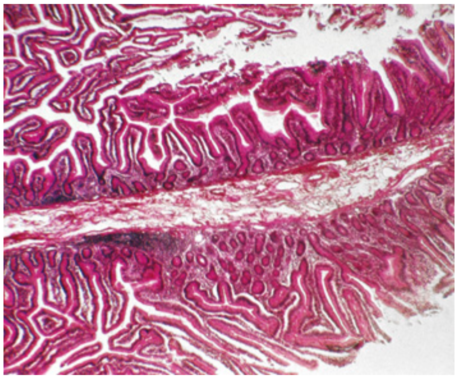
FIGURE 5.3.9 Cross-section of a villus from the small intestine. Villi are finger-like projections from the wall of the small intestine that increase the surface area for more efficient absorption of nutrients. Villi are covered in microvilli, which further increase the surface area for absorption.

Absorption in the small intestine

The epithelial lining in the small intestine is only one cell thick. This allows a rapid transfer of nutrients to the many blood and lymphatic vessels beneath the surface, which transport nutrients away to the body tissues. Nutrients pass through the lining of the small intestine by facilitated diffusion or active transport, along or against the concentration gradient.

Lipid-soluble molecules, which are the products of fat digestion (fatty acids and glycerol), diffuse easily through the membranes of the epithelial cells along a concentration gradient. They then reassemble into fats before passing into the **lacteals**. Lacteals are capillaries of the lymphatic system near the intestine. They have a milky appearance, because of their high fat content after a fatty meal has been eaten. Lipid-soluble vitamins also pass through the intestinal epithelium by passive diffusion.

Water-soluble molecules, including amino acids, simple sugars (monosaccharides, e.g. glucose), and water-soluble vitamins and minerals pass through the membranes of the epithelial cells by active transport and facilitated diffusion. This can occur down or against a concentration gradient, ensuring that these essential nutrients are absorbed quickly.

Most of the water (90–95%) that enters the small intestine is also absorbed. This absorption is passive. Water diffuses across the lining of the intestine osmotically as the products of digestion are absorbed.

Blood leaving the intestine passes first into the liver through the hepatic portal vein. Here, absorbed nutrients are removed and stored in the liver before the blood passes into the general venous circulation.

BIOFILE PSC

Good bacteria in the gut

Bacteria play a vital role in our digestive system. Without them, our bodies would not function correctly. The key to optimal digestive function is maintaining digestive balance. This means that beneficial bacteria outnumber potentially harmful bacteria. Probiotics are live, beneficial bacteria that are added in high numbers to food and beverage products to improve the balance of good bacteria within the digestive system. Probiotics are available from different sources, including fermented milk drinks, yoghurts, capsules and powders. Most bacteria used in food production are lactic acid bacteria, such as species of *Lactobacillus* and *Streptococcus* (Figure 5.3.10).

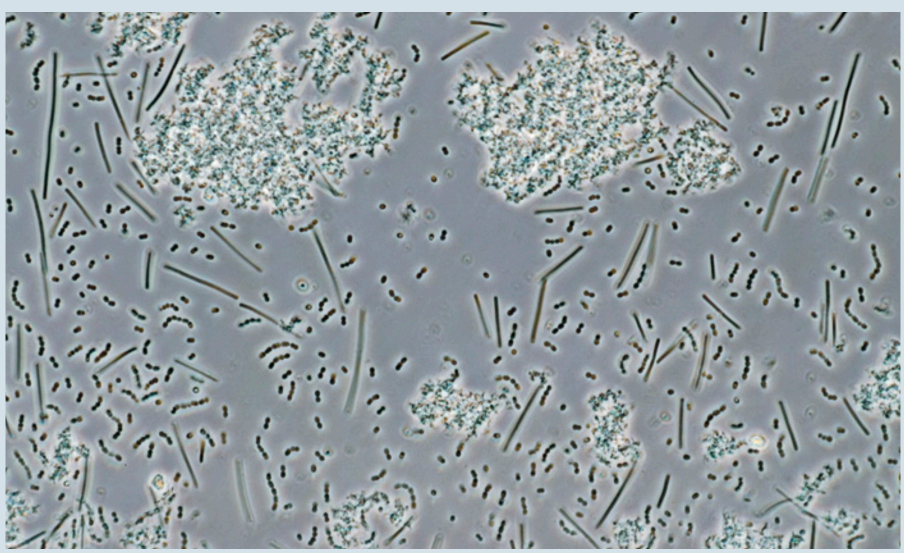

FIGURE 5.3.10 Phase contrast light micrograph of lactic acid bacteria—*Lactobacillus* and *Streptococcus*. These lactic acid bacteria are commonly used in the production of yoghurt.

Food and energy storage in mammals

When food is not available, an animal's body draws on its own stores to meet its nutritional and energy needs. Energy storage is essential for carnivores, which can only eat intermittently depending on the availability of prey.

Herbivores often travel considerable distances to find new and adequate supplies of edible plants when the seasons change, or if they have overgrazed an area. In winter, food generally becomes scarce for both herbivores and carnivores. In cold climates, animals need to consume more food to produce enough energy to maintain their body temperature. For example, freshly shorn sheep need to eat approximately 25% more food than normal, because without their fleece, their insulation against heat loss has been greatly reduced (Figure 5.3.11). In very cold climates, some mammals (usually small species) resort to hibernation to survive the winter (Figure 5.3.12). In each of these situations, the ability to store nutrients and energy reserves is essential for survival.

FIGURE 5.3.11 Shorn sheep need to consume more food than sheep with fleece to produce enough energy to maintain their body temperature.

Energy reserves

In contrast to plants, animals have only a limited capacity to store carbohydrates. The storage carbohydrate in animals is **glycogen**. Like starch, glycogen is a large molecule made from glucose subunits. When needed, carbohydrate stores are used first and most easily. In humans, about 300 g of glucose is stored as glycogen in the liver and muscles. This is enough to provide the energy for about half a day at a moderate level of activity. The remainder of our energy reserves is stored as fats.

Animals use fats rather than carbohydrates as their main form of energy reserves because:

- almost 25% more ATP is produced (per carbon atom) from fats compared with carbohydrates
- fat is almost 50% lighter (per carbon atom) than carbohydrate
- stored carbohydrates attract and bind water molecules, increasing their weight by 200–500%; fats do not
- 1 g of carbohydrate or protein provides up to 17 kJ of energy, while 1 g of fat provides 39 kJ of energy.

The capacity for storage in fat tissue (adipose tissue) is virtually unlimited. An average 70 kg male human stores about 11 kg of fat, which provides enough energy to last about a month without eating food. The same amount of energy stored as carbohydrate could weigh more than 100 kg.

BIOFILE S

Saving up for winter

Mountain pygmy possums (*Burramys parvus*) are Australia's only hibernating marsupials (Figure 5.3.12). They live in alpine areas in Victoria and hibernate under the snow during winter. Adults weigh only 45 g (equal to two Tim Tams) but they double their weight before entering hibernation by feeding on Bogong moths (*Agrotis infusa*) in spring and summer.

Mountain pygmy possums need a thick blanket of snow for insulation during their hibernation period, but climate change and reduced snowfall means that they may be exposed to low temperatures for longer periods. If their winter fat stores run out before the end of a longer hibernation, they could starve.

FIGURE 5.3.12 The mountain pygmy possum (*Burramys parvus*) is Australia's only hibernating marsupial. They accumulate fat stores before entering hibernation for 5–7 months every year.

Some of the chemical processes that take place in living organisms use up energy, while other processes release energy. For energy balance, energy input (eating) must equal energy output (usage). If the amount of food eaten provides more energy than is used, the excess energy is stored as chemical energy (e.g. in fat or glycogen). If the energy content of food is less than required, the balance is made up from stored energy reserves or by breaking down body tissues.

Unlike carbohydrates and fats, amino acids cannot be stored in animal tissues. The full range of amino acids needed for building proteins must be available in an animal's diet, because cells assemble proteins by linking amino acids in a specific order. If the next amino acid required is not available, the synthesis of that protein molecule cannot continue until the required amino acid arrives.

This has consequences for strict vegetarians. Unlike meat, individual plants do not normally contain the full range of essential amino acids. However, a vegetarian can obtain a balanced diet by eating an appropriate combination of plant foods in the same meal, such as beans (which are a good source of the amino acids isoleucine and lysine, but deficient in tryptophan) and rice (which is deficient in isoleucine and lysine, but a good source of other essential amino acids). A meal of rice and beans together is as good a source of protein as eggs or meat.

Energy requirements of humans

In animals, the amount of energy needed each day depends on factors such as basal metabolic rate, body size, activity level and environmental temperature. Metabolism is the name for the sum of all these processes, and metabolic rate is a measure of the overall energy requirements of an organism.

Basal metabolic rate refers to the amount of energy required to maintain basic functions in a resting, unstressed animal per unit of time. It varies greatly between species. Mammals have a much higher basal metabolic rate than some other vertebrates, because they use energy to maintain a constant body temperature. Basal metabolic rate does not include the extra energy required for activity or for maintaining a warm body temperature in a cold climate.

In humans and other mammals, metabolic rate is affected by:

- body composition (the proportion of fat or bone to muscle)
  - muscle tissue uses energy at a faster rate than does fat tissue, so more muscle means a greater energy requirement
- level of activity
  - different levels of physical activity account for large differences in metabolic rate
  - individuals vary in the amount of energy they use to carry out a particular activity
- biological sex
  - males generally use energy at a higher rate than females, mainly because on average they have a lower fat-to-muscle ratio than females
- age
  - metabolic rate increases during periods of growth, such as childhood and adolescence and levels off during adulthood (except during pregnancy and breastfeeding, when metabolism and energy requirements increase by approximately 25%)
  - metabolic rate declines during later years, mainly because of decreased physical activity and changes in body composition.

PA 2.2 WS 2.6

Malfunctions of the digestive system

The digestive system is complex. Many different functions must coordinate to digest food. Sometimes problems can arise in the digestive tract, inhibiting the absorption of nutrients. These problems can lead to minor or serious diseases, some of which can be treated with surgery or medication.

Coeliac disease

Coeliac disease affects both children and adults. It is a condition in which the villi of the small intestine are damaged (Figure 5.3.13) by the body's immune system in response to gluten, the protein found in wheat, rye, barley and other cereals. The damaged villi will repair themselves if affected individuals follow a gluten-free diet.

FIGURE 5.3.13 Villi damaged by coeliac disease

Liver disease

People who drink alcohol excessively are prone to severe and often fatal liver disease. Medical evidence indicates that the addition of vitamins to alcoholic drinks, while good for nutrition, will not prevent chronic liver damage.

Alcohol is a toxic substance. The enzymes that are needed to break it down are found in the liver. Because the biochemical pathways in the liver cells of a heavy drinker are involved with removing alcohol, the cells cannot carry out their normal levels of cellular respiration. Substances that should have been broken down for energy are converted to fats instead, and these fats accumulate in the liver.

For a while, the situation is reversible. But then the cells filled with fat start to die, causing alcoholic hepatitis. This is followed by cirrhosis, which is the formation of scar tissue in the liver (Figure 5.3.14). Finally, death may occur when the liver is unable to carry out its normal functions.

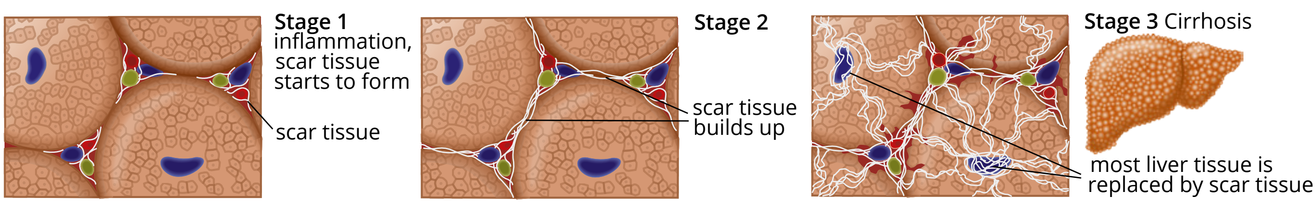

FIGURE 5.3.14 The stages of scar tissue formation (cirrhosis) in the liver. Tissue inflammation (Stage 1), followed by cell death, leads to scar tissue build up (Stage 2). Scar tissue replaces healthy tissue and eventually causes cirrhosis of the liver (Stage 3). Excessive alcohol consumption can cause this form of liver damage.

BIOFILE EU ICT

Virtual dissections

Over the course of history, animal dissections have been an important way for humans to investigate the complexity of organisms. Early investigations that used animal dissections advanced our understanding of the anatomy and physiology of living things and made progress in medicine possible.

Animals are still an important part of scientific research today. However, the use of animals in research is not always necessary. With today's technology, virtual dissections can be used to investigate the internal workings of organisms such as frogs, pigeons and rats, without using a dead specimen (Figure 5.3.15).

The three Rs of animal welfare—Replacement, Reduction and Refinement—should be used as a guiding principle when using animals in research. Virtual dissections can reduce the number of animals used for dissections and could potentially replace real animal dissections in school and university laboratories.

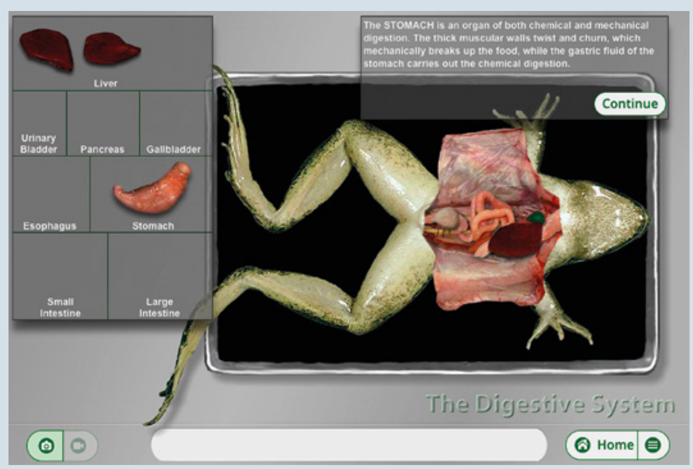

FIGURE 5.3.15 Virtual dissection of frogs can reduce the need for real animals in educational laboratories.

5.3 Review

SUMMARY

- Mammals are heterotrophs. They must consume other organisms or their products to obtain organic molecules.
- The purpose of digestion is to rapidly break down organic food into molecules small enough to be able to pass through cell membranes and into cells to produce energy.
- Physical breakdown of large food into smaller pieces increases the surface area available for enzyme action and increases the efficiency of digestion.
- Chemical digestion involves breaking apart complex molecules into simple molecules by the action of enzymes (amylase, protease and lipase).
- Animals have specialised teeth, digestive tracts and feeding behaviours that are adapted to meet their dietary requirements.
  - Carnivores have teeth that are specialised for tearing meat and short digestive tracts.
  - Herbivores have flat teeth for crushing and grinding plant matter and long digestive tracts to improve the digestion and absorption of cellulose.
  - The digestive tracts of some herbivores have bacteria that produce cellulase to break down the cellulose in plant cell walls.
  - Omnivores have digestive tracts that are longer than those of carnivores but shorter than those of herbivores.
- When food is not available, an animal's body draws on its own stores to meet its nutritional and energy needs.
- Mammals can store excess carbohydrates and fats, but not amino acids. Lipids store more energy by weight than carbohydrates.
- For energy balance, energy input (eating) must equal energy output (usage).
- The amount of energy that is needed each day depends on factors such as basal metabolic rate, body size, activity level and environmental temperature. In mammals, body composition, activity levels, sex and age also affect basal metabolic rate.
- Malfunctions of the digestive system include coeliac disease and liver disease.

KEY QUESTIONS

1 What are two differences between the digestive systems of herbivores and carnivores?

2 The small intestine is a site of absorption.
   a Describe the features of the small intestine that make it well suited to its absorptive role. Use diagrams to illustrate your answer.
   b What is different in the absorption of the products of fat digestion compared with the absorption of other products?

3 Compare the relative sizes of the stomach, small intestine, caecum and first part of the large intestine of hindgut fermenters with foregut fermenters.

4 What is the difference between foregut fermentation and hindgut fermentation?

5 **a** From a nutritional point of view, what is the problem for hindgut fermenters?
   b How do some hindgut fermenters overcome this problem?

6 Unlike carbohydrates and fats, amino acids cannot be stored in animal tissues. Why is this important from a dietary perspective?

7 List and describe three factors that affect the metabolic rate in humans.

8 Describe how the structure of the small intestine allows for rapid absorption of nutrients.

5.4 Gas exchange: heterotroph respiratory systems

Organisms must exchange oxygen and carbon dioxide with their environments to maintain the important energy-transforming process of cellular respiration. Disruption of this exchange—for example, by respiratory illness in humans—can have serious consequences.

In organisms that use **aerobic respiration**, the rate at which oxygen is supplied to cells limits the amount of energy that can be released from glucose for cellular activities. Carbon dioxide, which is produced as a waste product during cellular respiration, forms a weak acid in solution with water. If carbon dioxide accumulates in the body fluids, the pH will decrease (that is, acidity will increase), with damaging effects on the structure and function of many important molecules. It is therefore important that carbon dioxide is removed efficiently.

In unicellular and very small organisms with high surface area to volume ratios, adequate levels of gas exchange occur directly with the environment. In larger animals that have a high metabolic rate and a need for highly efficient gas exchange, well-developed mechanisms to ventilate their gas exchange surfaces are required. The gas exchange surface is linked closely to blood transport systems, ensuring that gases move efficiently between cells and the environment.

DIFFUSION

Gas exchange always takes place by **diffusion** across a moist cell membrane. Diffusion is the passive movement of a substance along its concentration gradient from a region of high concentration to a region of low concentration.

The immediate environment of cells is the layer of fluid that surrounds them. Even for organisms that get their oxygen from air, oxygen must first dissolve in the layer of extracellular fluid covering the gas exchange surface before it can cross cell membranes and enter the body.

Small, uncharged molecules, such as oxygen and carbon dioxide, pass directly through the phospholipid bilayer of the membrane. They therefore diffuse into or out of cells along their concentration gradient. In contrast to the many nutrients that are actively taken up by organisms, neither oxygen nor carbon dioxide is actively pumped across membranes.

The rate of diffusion of a molecule across a membrane depends on the size and maintenance of the concentration gradient, and on properties of the membrane itself. The amount of a certain molecule transferred per unit time depends on the membrane's permeability to the molecule, the available surface area of the membrane, and the thickness of the membrane (the distance of diffusion).

EFFICIENT GAS EXCHANGE SURFACES

For efficient gas exchange:

- the surface area should be as large as possible. There is a greater total exchange across a large surface than across a small one
- the barrier to be crossed (such as cell membranes and fluid layers) should be as thin as possible and should consist of a material that allows the gas to pass through the barrier easily
- there should be an adequate supply of the gas being transferred. If the respiratory surface is not adequately ventilated, the rate of exchange drops
- there should be efficient removal of the substance after transfer. Oxygen is carried away from the respiratory surface, usually by blood. Inadequate blood flow past the respiratory surface will allow oxygen to accumulate, slowing further transfer.

In most large animals, energy is required to ventilate the respiratory surface and circulate blood past its inner surface. The efficient supply and removal of oxygen maintains a high concentration gradient across the exchange surface, and therefore a high rate of diffusion.

Energy expenditure is most economical when the rates of **ventilation** and blood flow to the respiratory tissue are matched. For example, when you begin to exercise, you need more oxygen. You breathe more heavily and your heart rate increases. Ventilation and blood flow to the lungs are still matched, but each is at a higher level to supply more oxygen.

BREATHING AIR

When you breathe air, oxygen is absorbed from the environment by the respiratory system and transferred to your cells via the circulatory system.

The key steps in the process of human respiration occur at the following sites: nasal cavity, airways and **alveoli** (Figure 5.4.1).

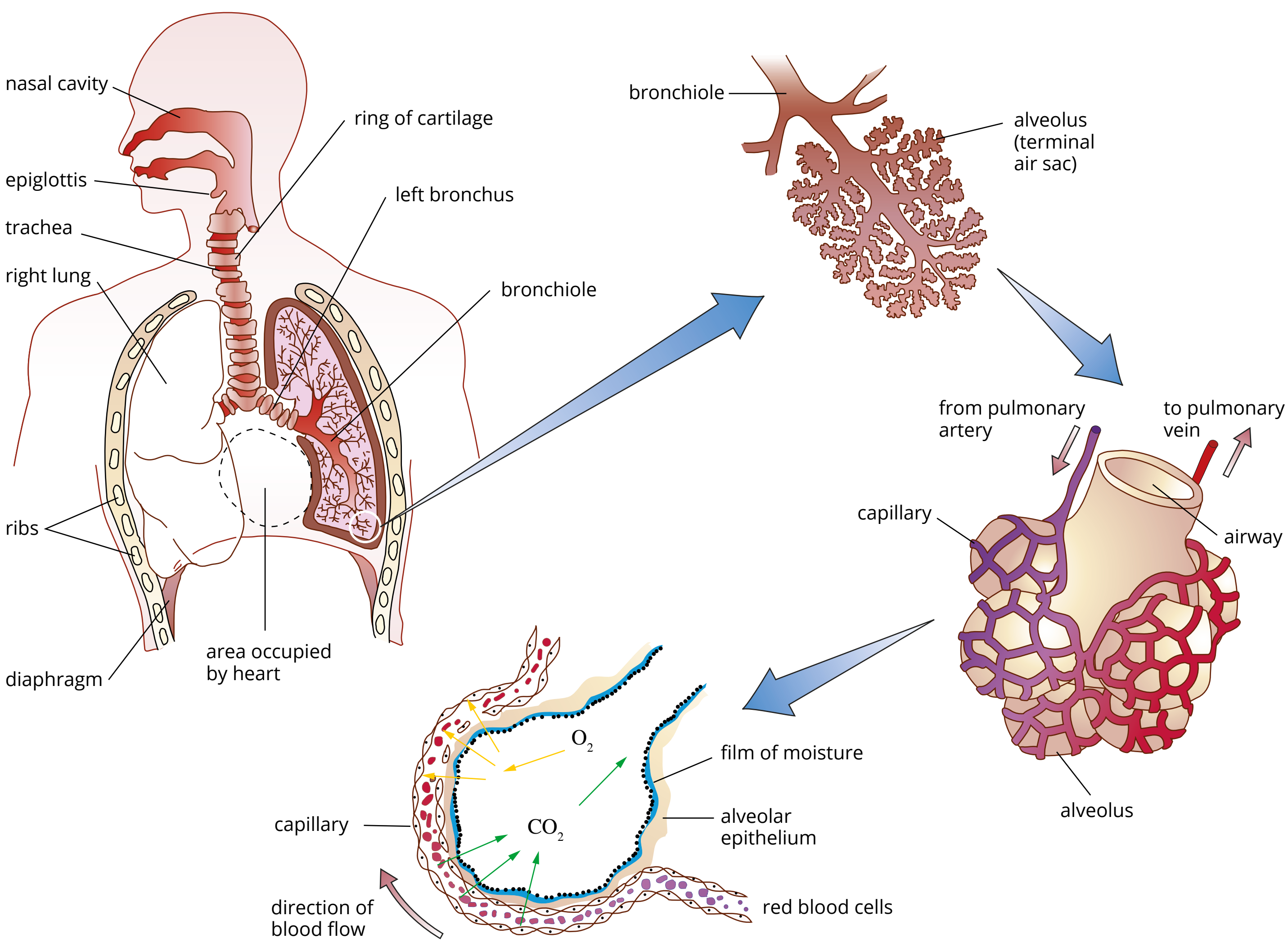

FIGURE 5.4.1 Structure of the human respiratory system

- Nasal cavity—Air is drawn in through the nose and passes into the nasal cavity and **pharynx** (the back of the throat). Breathing through the nose is preferable to breathing through the mouth because the air is filtered, moistened and warmed in the nasal passages.
- Airways—From the pharynx, air passes into the airways: the **trachea**, paired bronchi (singular **bronchus**) and branching **bronchioles**. The trachea and bronchi are lined with cells covered in cilia (singular **cilium**) and secrete mucus (Figure 5.4.2). Particles of dust or bacteria are trapped by this mucus and swept by the cilia back up to the pharynx and swallowed.
- Alveoli—Air enters the terminal air sacs, called alveoli, where gas exchange takes place. A constant supply of oxygen to cells is the most critical input for endotherms, such as mammals and birds, because they use energy to warm their bodies, and therefore need oxygen at a great rate for cellular respiration.

The alveoli have many specialised features that make them efficient gas-exchange structures. Alveoli provide a large surface area for gas exchange; the total surface area in most adults is between 30 and 70 m^2. Each alveolus is lined with a very thin layer of flattened cells, called the alveolar epithelium (Figure 5.4.1). This thin layer of cells is richly supplied with blood capillaries, facilitating diffusion of gases between the alveoli and the capillaries (Figure 5.4.1). Once oxygen enters the capillaries, it has entered the circulatory system, and the oxygenated blood is transported throughout the body (Figure 5.4.3).

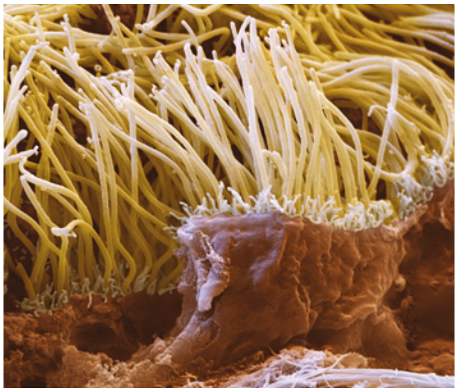

FIGURE 5.4.2 A cross-section through the cilia-covered epithelial cells of the bronchus (lung airway). The cilia are microscopic hairs that sweep trapped particles and mucus away from the gas-exchanging parts of the lungs and towards the throat, where the particles can be swallowed or coughed up.

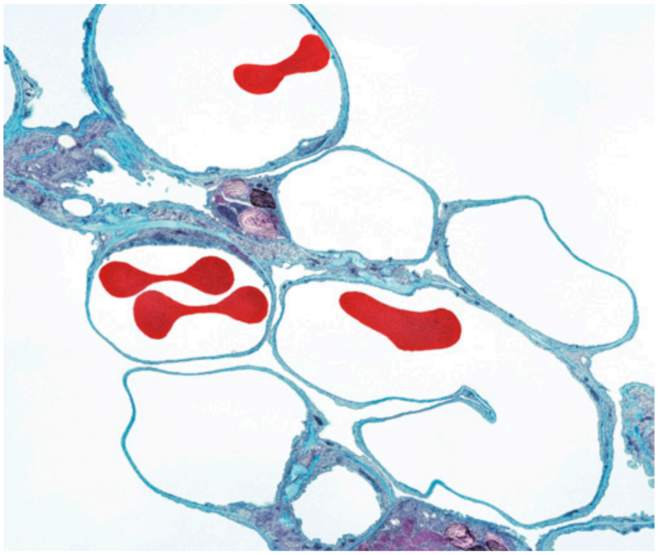

FIGURE 5.4.3 Lung alveoli and red blood cells. Coloured TEM image of a section through lung alveoli (blue) and red blood cells (red). Alveoli are the site of gaseous exchange in the lungs, where oxygen is taken up by the red blood cells and carbon dioxide is released for exhalation.

Breathing air has advantages and disadvantages. Ventilation with air requires much less energy than breathing water, which is heavy, and much more oxygen is available in air than is available in water. But animals that breathe air must have a large, moist gas exchange surface. Because water evaporates continuously from this surface, it is a major site of water loss for all terrestrial organisms.

Enclosing the respiratory surface inside the body provides physical protection from the external environment, supports the respiratory membrane, and reduces water loss. However, it increases the need for efficient ventilation of the gas exchange surface.

> Ventilation (breathing) is the active movement of the respiratory medium (air or water) across a gas exchange surface.

Lung ventilation

Mammalian lungs are contained in the chest cavity (the thorax). The thorax is completely enclosed and under a small negative pressure that keeps the lungs expanded. The floor of the chest cavity is the muscular **diaphragm**.

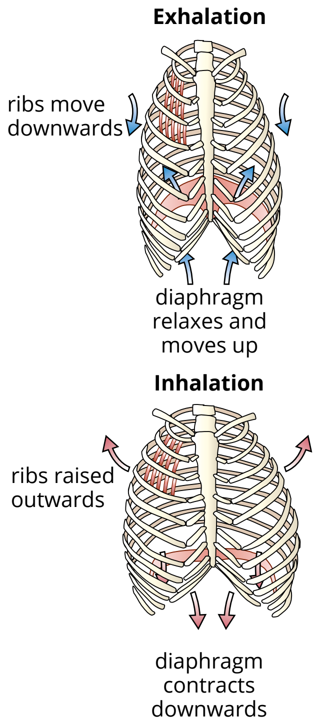

FIGURE 5.4.4 Mammals breathe by negative pressure ventilation. Raising the ribs and contracting the diaphragm increases the volume of the chest cavity and draws air into the lungs (inhalation). Relaxing these muscles reduces the volume of the chest cavity, forcing air out (exhalation).

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FIGURE 5.4.5 A diver wearing high-pressure breathing apparatus

WS 2.7

Mammals use a 'suction pump' mechanism to ventilate their lungs. The chest cavity is expanded by the contraction of the diaphragm downwards and the raising of the ribs. This expands the lungs and draws air in through the airways (Figure 5.4.4). Inhalation is always an active process that requires energy. Exhalation, however, is normally the result of the elastic recoil of the thorax as it returns to its relaxed state. Forceful exhalation involves an active compression of the rib cage.

Human divers must breathe air at high pressure to inflate their lungs against the pressure of the outside water. This is because our chest muscles are not strong enough to expand the rib cage and inhale against water pressure at depths below about 1 m (Figure 5.4.5).

Tidal volume

Tidal volume is the volume of air moved in and out at each breath. Normal resting levels of inhalation and exhalation are much less than our **vital capacity**, which is the maximum volume of air that we can move into and out of our lungs. Tidal volume varies according to the need for oxygen.

Air moves tidally into and out of mammalian lungs through the same airways (Figures 5.4.4 and 5.4.6). This is not as efficient as one-way flow, because at the end of an exhalation there is still some 'stale' air left in the airways and in the alveoli. The next inhalation draws this stale air back into the lungs. Therefore, it is impossible to fill our lungs completely with fresh air. The volume of air left in the respiratory system at the end of exhalation is referred to as the residual volume.

You will learn more about the transport of gases between the internal and external environments of an animal in Chapter 6.

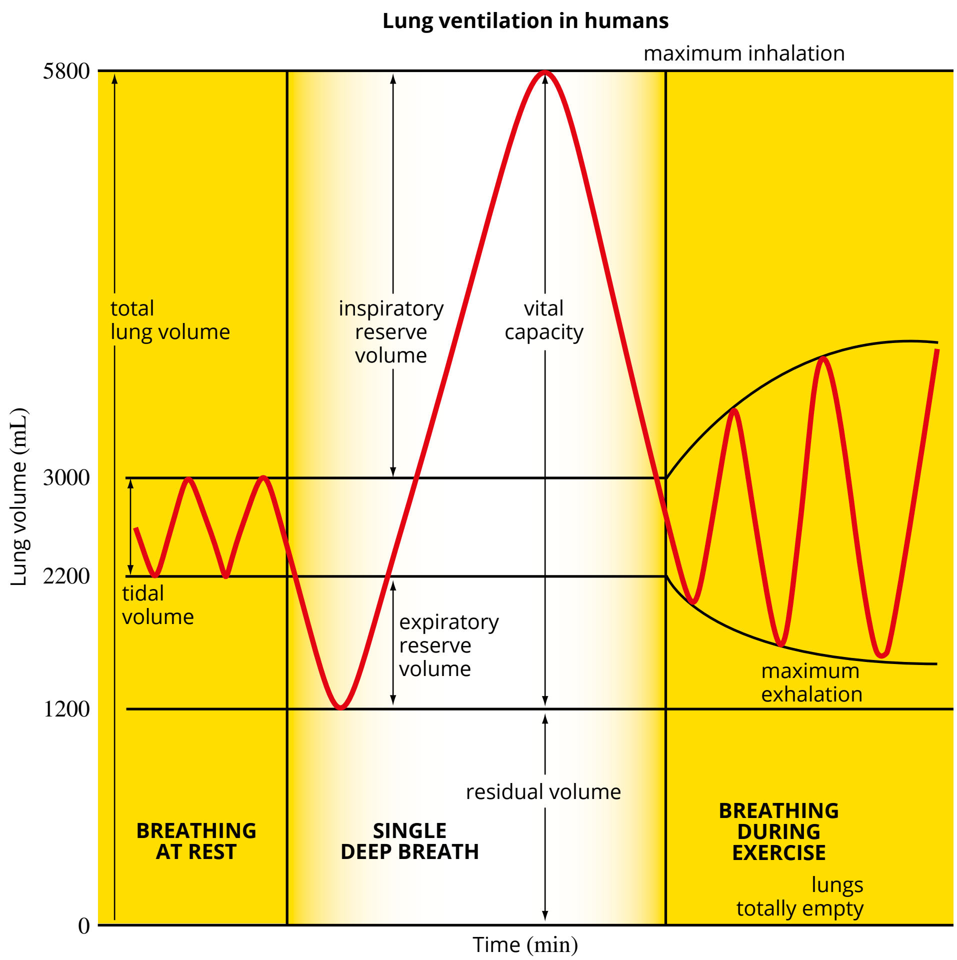


FIGURE 5.4.6 Lung ventilation in humans. During exercise, tidal volume increases. The extent of this increase is directly related to the increased use of oxygen, and is matched by an increased blood flow to the lungs.

MALFUNCTIONS OF THE RESPIRATORY SYSTEM

Asthma, **emphysema** and **pneumonia** are human illnesses of the respiratory system. Although these three illnesses are unrelated, some of their symptoms—such as tiredness and inability to exercise—are similar. Each illness interferes with at least one of the important features responsible for efficient gas exchange in the lungs, leaving the cells unable to produce enough energy for their normal functions.

Asthma

Asthma is a condition in which the cells lining the airways (bronchi and bronchioles) are sensitive to foreign particles in the air, such as pollen. Small airways swell, fill with mucus and become constricted (Figure 5.4.7). This reduces the space through which air can flow, increasing the resistance to the flow of air into and out of the lungs. It is particularly difficult to breathe out. When the pressure on the lungs is increased to force air out, the narrowed airways causing the obstruction are also compressed.

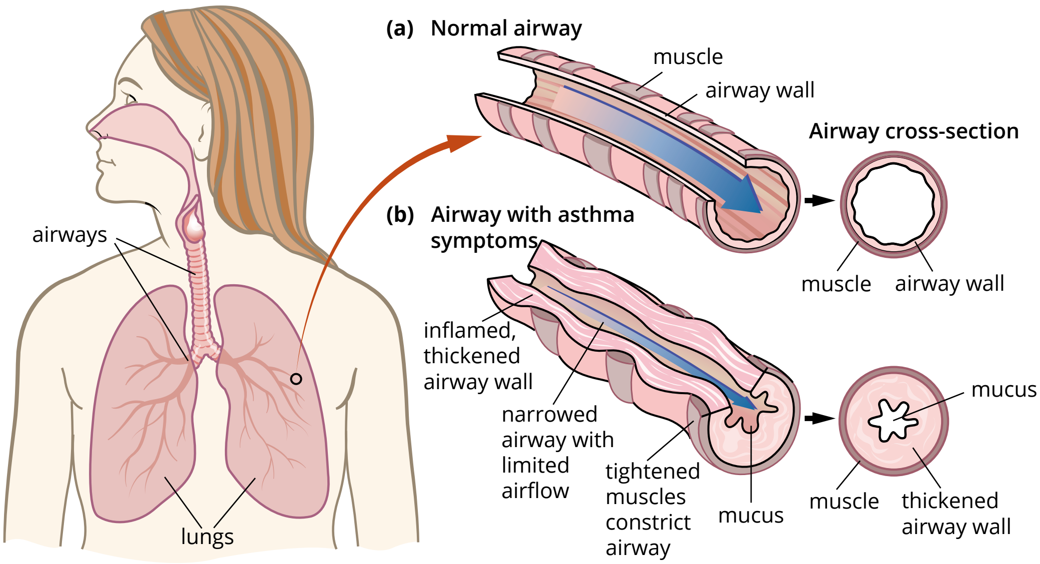


FIGURE 5.4.7 An overview of the respiratory system in humans, with a comparison of (a) normal airways and (b) inflamed airways during an asthmatic episode

Emphysema

Emphysema is caused by the breakdown of air sacs in the lungs. This reduces the lung surface area available for gas exchange, sometimes to less than one-quarter of that of healthy lung tissue (Figure 5.4.8). It occurs mostly in older people and is becoming increasingly common, most likely due to smoking (Figure 5.4.9). Like asthma, emphysema involves an increased resistance to airflow in the small airways, making breathing more difficult.

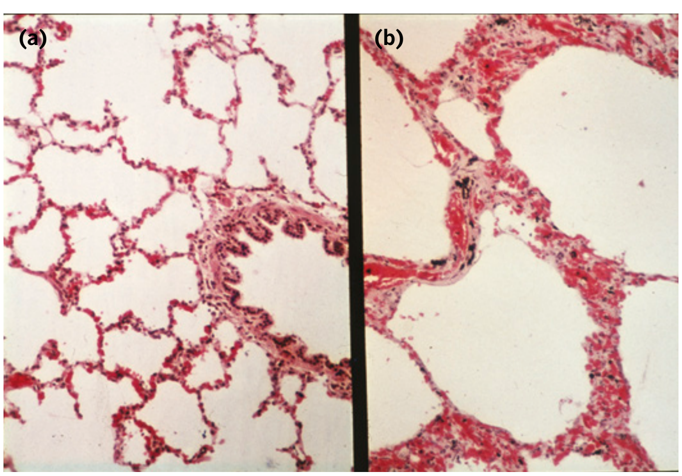


FIGURE 5.4.8 (a) Normal lung tissue has many small air spaces (alveoli) and very thin membranes for efficient gas exchange. (b) In the lungs of a person with emphysema, the walls of the alveoli break down and the membranes become thicker. In this case, the emphysema was associated with inhalation of coal dust, some of which is seen as black deposits (anthracosis) in the lung tissue. Both light micrographs were taken at the same magnification.

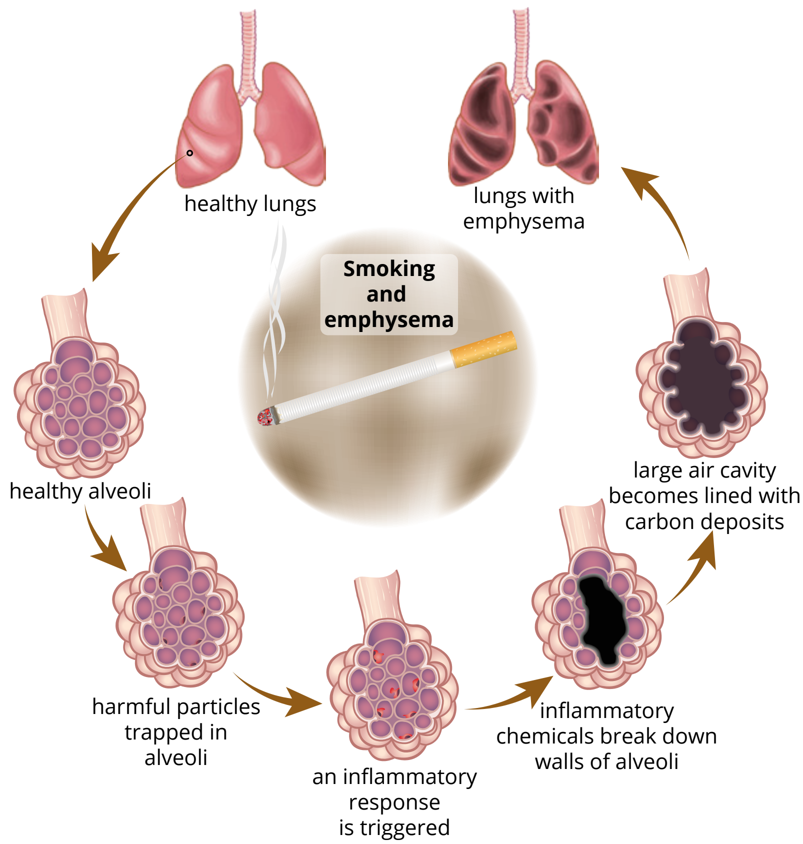


FIGURE 5.4.9 The stages of emphysema caused by smoking. Emphysema is a progressive disease, with inflammation and breakdown of the alveoli worsening over time with exposure to cigarette smoke.

Pneumonia

Pneumonia is caused by an infection that causes the lungs to become inflamed, and the air sacs (alveoli) to fill with white blood cells and fluid (Figures 5.4.10 and 5.4.11). This interferes with respiration, because the fluid in the alveoli reduces the area of lung surface in contact with air. The inflamed lung tissue is also swollen, so that oxygen must diffuse further before it can enter the blood.

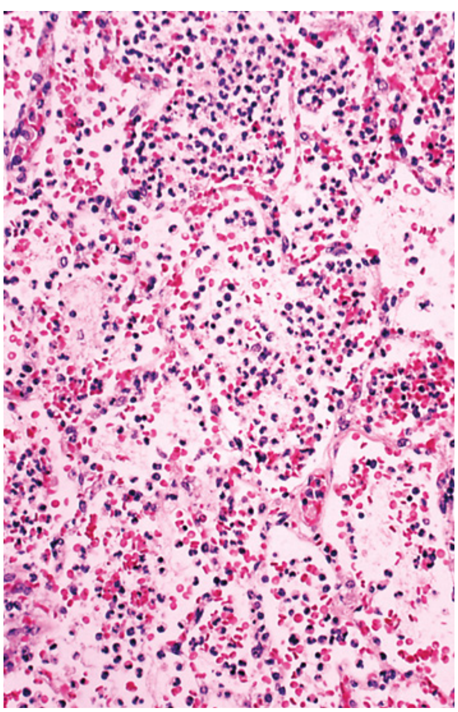


FIGURE 5.4.11 Light micrograph of lung tissue from a person with pneumonia. Pneumonia is caused by an infection that leads to the alveoli becoming inflamed and filled with fluid and white blood cells.

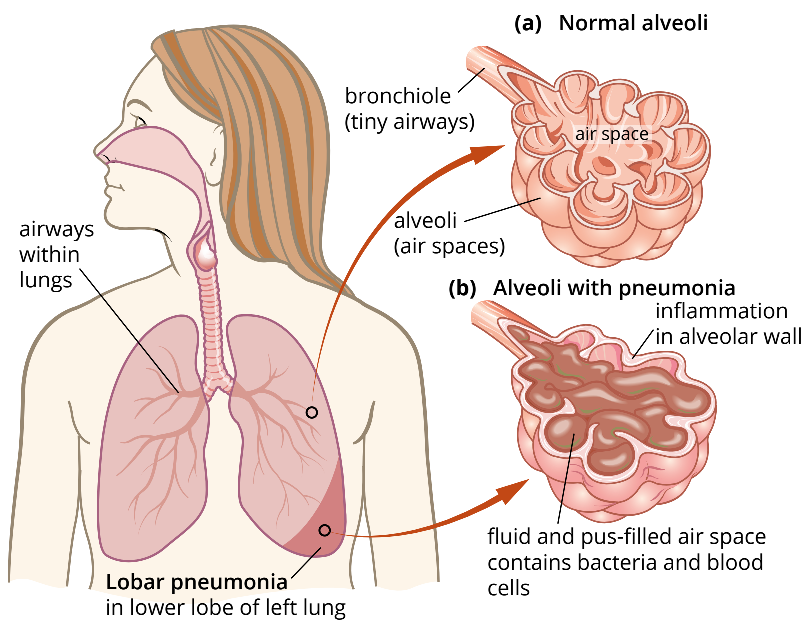


FIGURE 5.4.10 An overview of the respiratory system in humans with (a) a comparison of normal alveoli and (b) the inflamed, fluid-filled alveoli of a person with pneumonia

5.4 Review

SUMMARY

- Efficient gas exchange requires a large, moist surface area; a thin barrier; and an adequate supply and removal of the transferred gas.
- The mammalian respiratory system consists of the pharynx, trachea, bronchi, bronchioles and alveoli.
  - alveoli (singular alveolus) are the sites of gas exchange
  - each alveolus is lined with a very thin layer of flattened cells that have a rich supply of capillaries, making diffusion of gases between the alveoli and the capillaries very efficient
  - the many small alveoli in the lungs create a large surface area for gas exchange
- Lung ventilation involves tidal inhalation and exhalation of air using a suction pump mechanism.
- Ventilation is the active movement of the respiratory medium (air or water) across a gas exchange surface.
- Ventilation rate can be measured using a spirometer.
- Malfunctions of the respiratory system include asthma, emphysema, lung cancer and pneumonia.

KEY QUESTIONS

1. What are two characteristics of an efficient gas exchange surface?
2. Arrange the following structures in the respiratory system in order from the largest in diameter to the smallest: alveolus, trachea, bronchiole, bronchus.
3. Outline the features of the alveoli that make them highly effective for gas exchange.
4. Why do people with asthma and emphysema have difficulty breathing?
5. Describe the term ‘tidal volume’.

Chapter review

05

KEY TERMS

adenine triphosphate (ATP)
aerobic respiration
alveoli
amino acid
amylase
anaerobic respiration
anus
asthma
autotroph
basal metabolic rate
bile
bronchiole
bronchus (pl. bronchi)
caecum
carbohydrate
carbon dioxide
carnivore
cellular respiration
cellulase
cellulose
chemical digestion
chemoautotroph
chemoheterotroph
chemosynthetic
chloroplast
cilium (pl. cilia)
coprophagy
diaphragm
diffusion
digestion
digestive enzyme
egestion
emphysema
endothermic
epiglottis
epithelial cell
essential amino acid
excretion
extracellular digestion
fermentation
flaccid
food vacuole
gall bladder
glucose
glycerol
glycogen
granum
guard cell
herbivore
heterotroph
hydrolysis
inorganic compound
intracellular digestion
invertebrate
lacteal
large intestine
larynx
lipase
lipid
liver
lumen
maltose
mesophyll
metabolism
methanogen
microvillus
mineral
mouth
oesophagus
omnivore
organic compound
oxygen
palisade mesophyll
pancreas
parasite
peristalsis
pharynx
phloem
photoautotroph
photoheterotroph
photosynthesis
physical digestion
pneumonia
protease
protein
rectum
rumen
ruminant
salivary gland
saprotroph
small intestine
spongy mesophyll
starch
stoma (pl. stomata)
stomach
stroma
thylakoid lamella
tidal volume
trachea
transpiration
transpiration–cohesion–tension theory
turgid
ventilation
vertebrate
villus (pl. villi)
vital capacity
vitamin
water
xylem

REVIEW QUESTIONS

1 Contrast photosynthetic autotrophs with chemosynthetic autotrophs.

2 Chemoautotrophs acquire energy from inorganic chemical reactions.

a Name one chemical conversion used by a chemoautotroph.

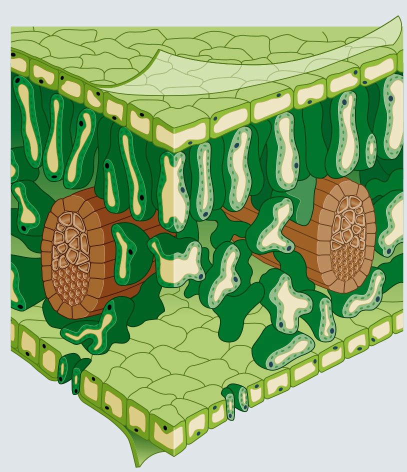
b Name one chemoautotroph and the organic compound it produces.

3 List the five types of heterotrophs, and then spend 30 seconds writing down as many examples as you can think of for each type.

4 Draw a table comparing photosynthetic autotrophs, chemosynthetic autotrophs and heterotrophs.

5 Which organelle is the site of photosynthesis?

6 **a** Identify the position of the stomata and guard cells on the diagram below.

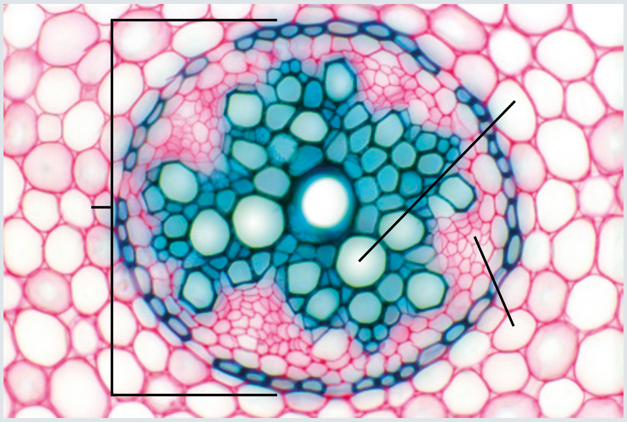


b Complete the table below, defining the following terms with reference to a plant.

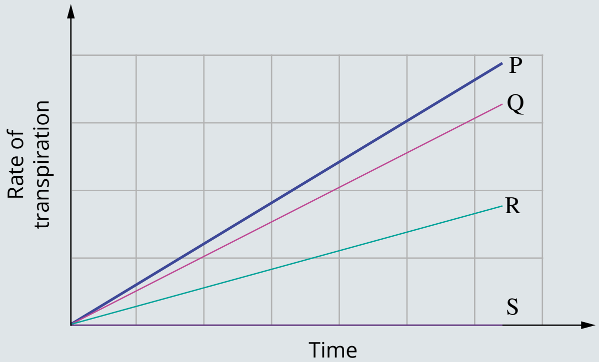
	Definition
turgid	
flaccid	
stoma	
epidermal layer	
guard cell	

c Describe the function of stomata in gas exchange and transpiration of a plant.

7 The image below is a cross-section of the root of a buttercup plant viewed under a light microscope. Label the parts of the root.



8 An experiment was conducted to determine the effects of applying a sticky gel to a leaf on the rate of transpiration. The graph below shows the results of the experiment.



Match each line labelled on the graph to the correct experimental condition (a, b, c or d).

a no gel applied

b gel applied to the lower side of the leaves

c gel applied to the upper side of the leaves

d gel applied to the lower side and the upper side of the leaves

9 Plant leaves contain guard cells and palisade cells. Explain how each of these kinds of cell assists photosynthesis.

10 List one environmental factor, other than light intensity and carbon dioxide concentration, that can limit the rate of photosynthesis.

11 An experiment was set up to investigate photosynthesis. A plant was placed in a sealed container at 20°C. The air in the container was 0.09% CO_2 at the beginning of the experiment. (CO_2 concentration in room air is between 0.03 and 0.04%.) The experiment was undertaken at three different light intensities—dim, moderate and bright. The CO_2 concentration in the container was monitored over a 4 hour period. The results for each light intensity were collected and are shown in the table below.

Time (min)	Light intensity		
	Dim	Moderate	Bright
0	0.090	0.090	0.090
30	0.084	0.080	0.080
60	0.076	0.070	0.070
90	0.069	0.060	0.054
120	0.060	0.053	0.045
150	0.054	0.045	0.038
180	0.048	0.038	0.030
210	0.041	0.030	0.027
240	0.039	0.027	0.021

a Draw a graph using the information in the table. Use the same set of axes for the three light intensities. Ensure that the graph complies with all graphing conventions.

b Describe the trends evident in the data.

c i Why can CO_2 uptake be used as a measure of the rate of photosynthesis?

ii Explain why CO_2 decreased the fastest in bright light.

d Why was the reduction in CO_2 the same for bright and moderate light until after 60 minutes had passed?

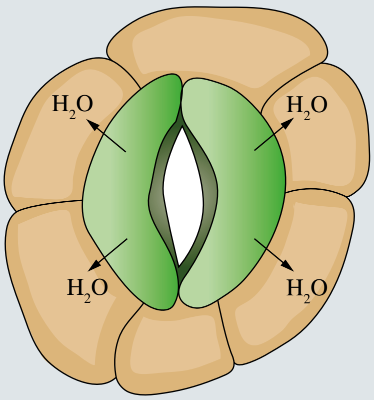
e Why were all the experiments carried out at 20°C?

f What hypothesis could this experiment have been testing?

g A second experiment was conducted using a CO_2 concentration of 0.03%. What would you expect to observe when comparing the results from the 0.09% CO_2 experiment with the 0.03% CO_2 experiment?

12 Compare the optimal temperature range for plants found in a tropical climate with plants from an arctic climate.

13 The figure below represents two guard cells, with surrounding epidermal cells, in the leaf of a plant. The plant is in bright light. The arrows on the diagram indicate the direction of the net movement of water from the guard cells into the epidermal cells. Describe what has happened to the potassium ions in this situation and if the stoma will open or close.



14 Wavelengths of light are often represented using scientific notation (e.g. 10^{-8}). Match each number on the left with its scientific notation on the right.

0.002	2×10^3
2000	1.234×10^{-1}
0.1234	2×10^{-3}
12.34	1.234×10^1
123.4	1.234×10^2

15 Which one of the following statements relating to fermentation in herbivores is true?

A In foregut fermenters, cellulose is digested in the caecum.

B Fermentation in the gut requires oxygen.

C The rumen is located between the oesophagus and the stomach.

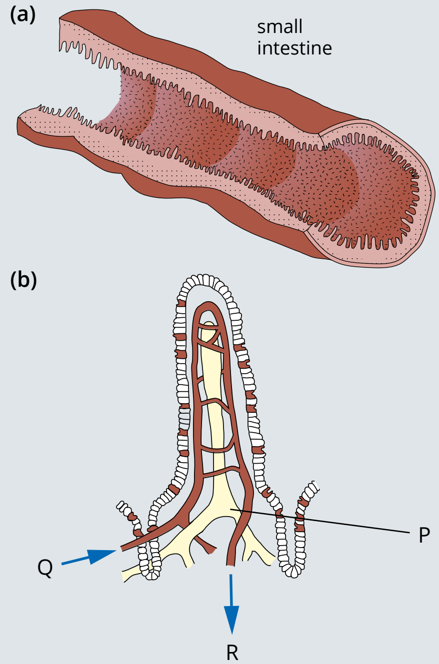
D All native Australian mammals are hindgut fermenters.

16 Figure (a) below shows a cross-section through the small intestine. Figure (b) shows a longitudinal section through a villus.

a Using Figures (a) and (b), outline three ways in which the structure of the small intestine is related to its function of absorbing the products of digestion.

b Referring to Figure (b), identify structure P and state its function.

c The arrows in Figure (b) indicate the direction of blood flow. State how the composition of blood entering from Q would be different from blood leaving R.



17 Which enzyme acts to break down lipids into fatty acids and glycerol?

18 List the sequence of organs that substances pass through as they move through the human digestive system.

19 Coeliac disease causes the destruction of villi cells. Which one of the following is most likely to happen to people with coeliac disease?

A damage in the oesophagus caused by increase in acid reflux

B incomplete digestion of proteins

C increased levels of glucose in blood

D poor absorption of calcium

20 An investigation was conducted to determine whether there is a relationship between tidal volume of normal breathing and vital capacity in a group of adults. The vital capacity is the maximum amount of air that can move into and out of the lungs. The volume exhaled in each case was measured by a spirometer. The tidal volume and vital capacity of seven adults was measured five times and the mean for each participant is given in the table below.

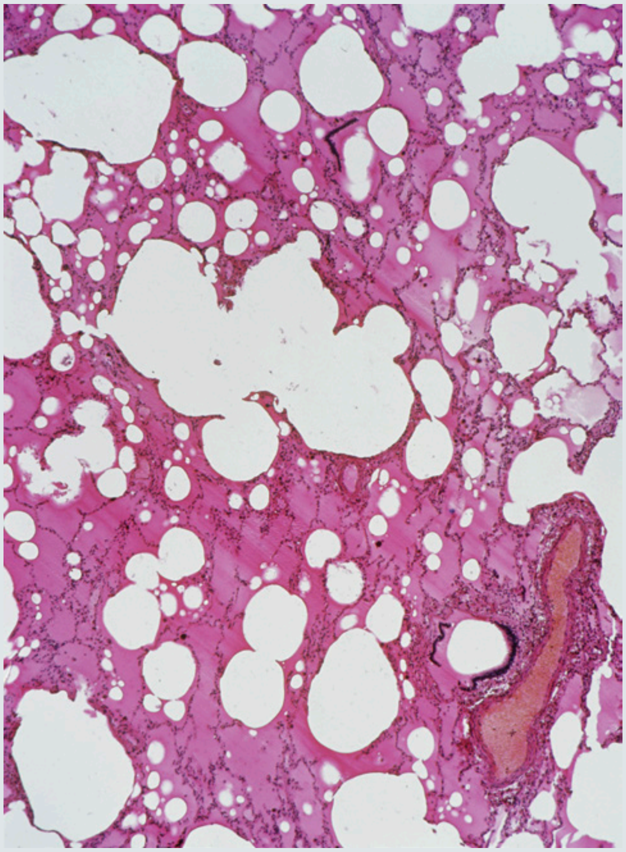
Individual	Tidal volume (cm^3)	Vital capacity (cm^3)
1	360	3890
2	400	4010
3	560	5100
4	380	3900
5	420	3300
6	435	3450
7	480	3250
8	510	4100
9	365	5000
10	499	4700

a State two variables that must be kept controlled in this experiment to make the data as reliable as possible.

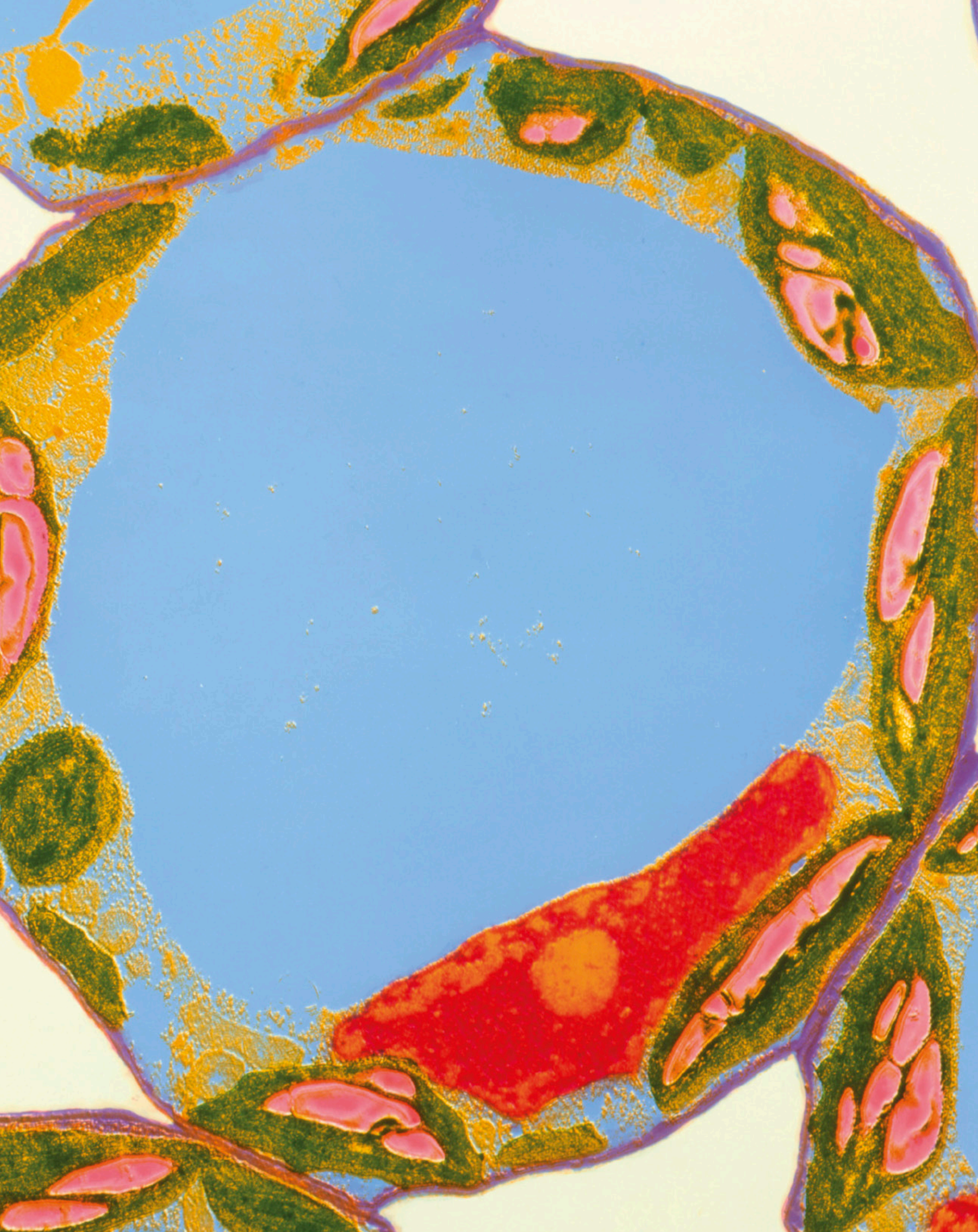
b Describe how the data could be presented to determine if there is a relationship between tidal volume and vital lung capacity.

c How might the data for tidal volume differ if the subjects had exercised before the measurements were taken?

21 This is a microscopic image of lung tissue. Use your knowledge of lung structure to determine if this tissue is from a healthy lung. Provide reasons to support your answer.



22 After completing the Biology Inquiry on page 228, reflect on the inquiry question: What is the difference in nutrient and gas requirements between autotrophs and heterotrophs? Using at least five key terms from this chapter, discuss how the different nutrient and gas requirements of organisms determine their role in the environment.



CHAPTER

06 Transport

Transport systems move nutrients, gases and wastes in and out of the cells of an organism. In vascular plants, xylem and phloem tissues throughout the roots, stems and leaves fulfil this role, while in animals, it is the cardiovascular and lymphatic systems. This chapter will introduce you to transport systems by comparing the microscopic and macroscopic structures that plants and animals use to transport nutrients and gases. You will compare the vascular systems of plants and animals and learn about the differences between the open and closed transport systems of animals.

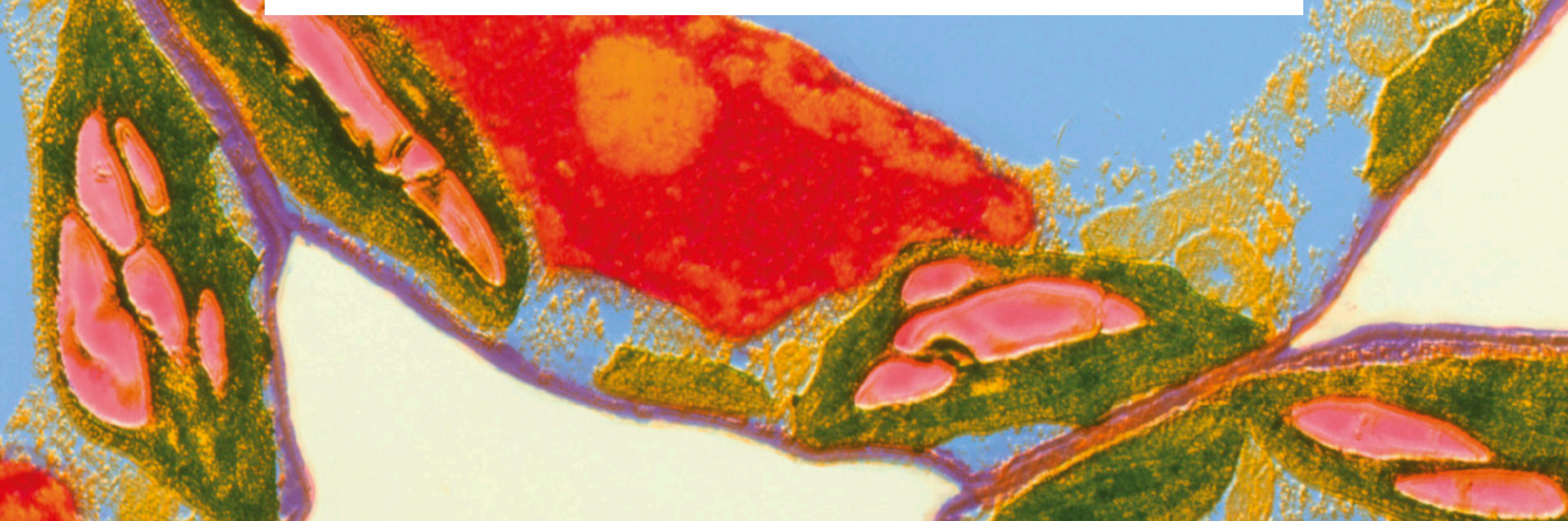
Content

INQUIRY QUESTION

How does the composition of the transport medium change as it moves around an organism?

By the end of this chapter you will be able to:

- investigate transport systems in animals and plants by comparing structures and components using physical and digital models, including but not limited to: (ACSBL032, ACSBL058, ACSBL059, ACSBL060) ICT L
  - macroscopic structures in plants and animals
  - microscopic samples of blood, the cardiovascular system and plant vascular systems ICT
- investigate the exchange of gases between the internal and external environments of plants and animals ICT L
- compare the structures and function of transport systems in animals and plants, including but not limited to: (ACSBL033) L
  - vascular systems in plants and animals
  - open and closed transport systems in animals
- compare the changes in the composition of the transport medium as it moves around an organism



6.1 Transport systems in plants

DS 2.1

BIOLOGY INQUIRY CCT

Colouring flowers using transport

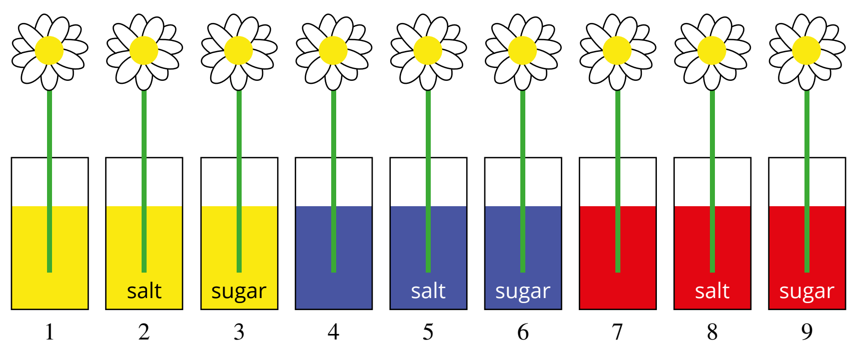
How does the composition of the transport medium change as it moves around an organism?

COLLECT THIS…

- 9 containers to hold flowers
- 9 white carnations
- red, blue and yellow food dye
- water
- measuring cup

DO THIS…

1 Cut the stem of each flower diagonally, making sure that each stem is the same length and longer than the containers you will put the flowers in.
2 Label the containers 1–9 and add 50 mL of water to each.
3 In containers 1, 2 and 3 add 20 drops of yellow food dye.
4 In containers 4, 5 and 6 add 20 drops of blue food dye.
5 In containers 7, 8 and 9 add 20 drops of red food dye.
6 Add 1 teaspoon of salt to containers 2, 5 and 8.
7 Add 1 teaspoon of sugar to containers 3, 6 and 9.
8 Put one flower in each container and leave the flowers in a sunny location for the next 72 hours.



9 Draw a table in your workbook to record your observations after 1 hour, 24 hours, 48 hours and 72 hours.

RECORD THIS…

Describe the appearance of each flower after 1 hour, 24 hours, 48 hours and 72 hours. You could also include diagrams or photos.

Present an explanation for any differences you observe between the flowers exposed to salt and sugar.

REFLECT ON THIS…

What is the role of the vascular system in transporting materials in a plant?

Why is it important for plants to control the movement of materials in and out of their cells?

How does the composition of the transport medium change as it moves around an organism?

As you learnt in Chapter 5, vascular plants—like all plants—are autotrophs, or producers. They manufacture their food from light energy by photosynthesis. For photosynthesis to occur, plants need water, carbon dioxide and sunlight for energy. Water is absorbed through the roots, and carbon dioxide is absorbed through the leaves. Photosynthesis occurs in the leaves and produces the sugars that are needed by all active cells of the plant.

In large vascular plants, the leaves can be a long way from the roots. Tall trees, such as the giant sequoia in Figure 6.1.1, need to transport water and nutrients up to 100 m from the roots to the upper branches. Transport of these substances to where they are needed is made possible by vascular tissue.

In this section you will learn about the systems and structures that plants use to transport water and nutrients.

FIGURE 6.1.1 The tallest trees in the world are the giant sequoias (*Sequoiadendron giganteum*) of California. These trees can reach a height of more than 95 m. Their root system is relatively shallow, but water still needs to travel a great distance from the roots to the leaves, where it is used during photosynthesis.

TRANSPORT STRUCTURES: VASCULAR TISSUE

Vascular tissue is used by vascular plants to transport water and mineral ions absorbed from the soil and sugars produced in the leaves to cells throughout the plant. Vascular tissue is visible as parallel veins in grasses, branching veins in many other leaves and the stringy parts of celery.

You learnt in Chapter 5 that vascular plants have two types of vascular tissue:

- **xylem**—transports water and inorganic nutrients (mineral ions) absorbed by the roots from the soil to the aerial (above ground) parts of the plant
- **phloem**—transports organic nutrients (dissolved sugars) produced in the leaves by photosynthesis throughout the plant. Other organic substances, such as amino acids, are also transported in the phloem.

GO TO ➤ Section 5.2 page 234

Xylem and phloem form continuous, closed tubular pathways through roots, stems and leaves (Figure 6.1.2). Fluids flow through these tubules to all parts of the plant. All cells are close to vascular tissue.

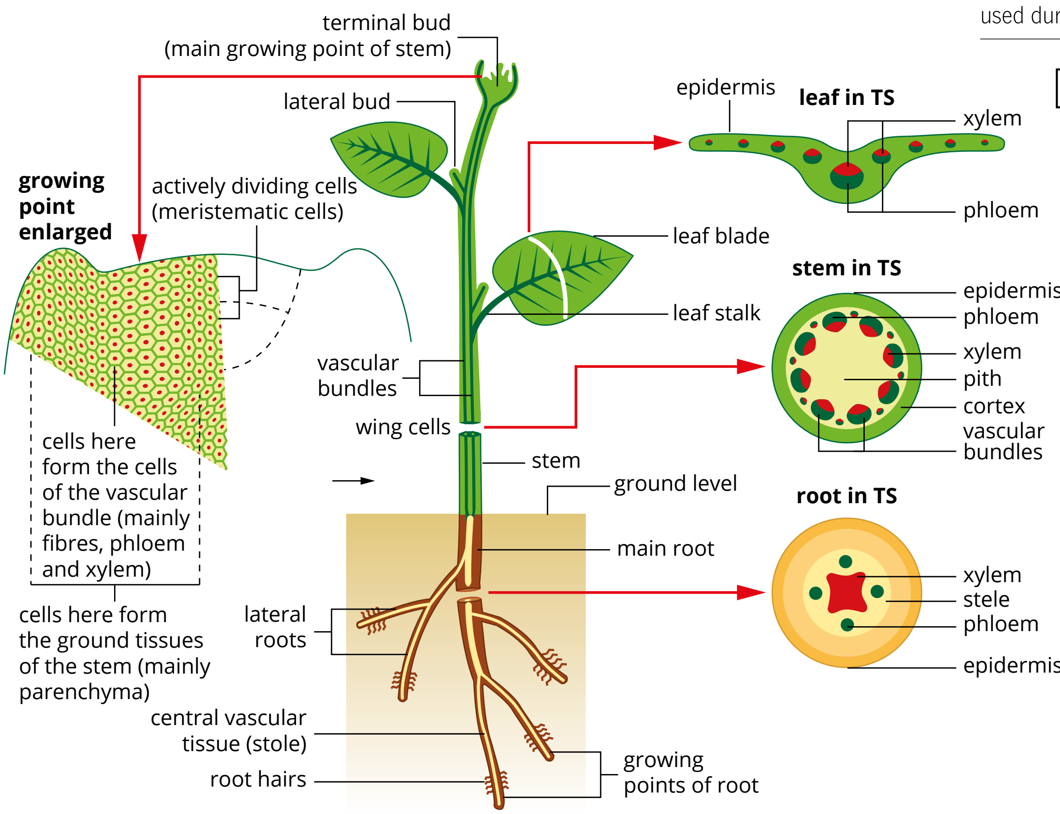


FIGURE 6.1.2 The main function of the plant transport system is to transport water and organic solutes from the roots to the leaves and to transport food manufactured in the leaves (sucrose and amino acids) to the other plant tissues. The transport system tissues—the xylem and phloem—are continuous, tubular pathways through the roots, stems and leaves. (TS: transverse section)

TRANSPORT OF WATER AND MINERAL IONS

Plants absorb the water and mineral ions they need for growth from the soil through their root hair cells. Potassium is needed to regulate the opening and closing of stomata; calcium is needed to build cell walls; magnesium is important in the production of chlorophyll; and nitrogen is necessary for making proteins and amino acids. Water is essential for dissolving and transporting mineral ions through the plant. Following absorption, the plant must transport water and mineral ions from the roots to where they are needed.

Xylem

Xylem is the vascular tissue that transports water and mineral ions obtained from the soil throughout the plant. It is mainly composed of **xylem vessels** and elongated cells called **tracheids**.

Xylem vessels

A mature xylem vessel (also known as a vessel element) is a long, water-filled tube consisting of elongated cells joined end to end (Figure 6.1.3). As the cells mature, the cell wall is strengthened with **lignin** (a polymer related to cellulose), making them stronger and more rigid. The cytoplasm and nucleus in the xylem vessel cells then disintegrate and the cells die, creating hollow lignin tubes.

Mature xylem vessels have:

- cylindrical skeletons of dead cells joined end to end to form continuous tubes
- perforated or complete openings at each end, like a straw, so that fluid can flow directly through them
- pits (unthickened areas) and perforations in the side walls that allow sideways movement of substances between neighbouring vessels in the **vascular bundle**
- no nucleus or cytoplasm.

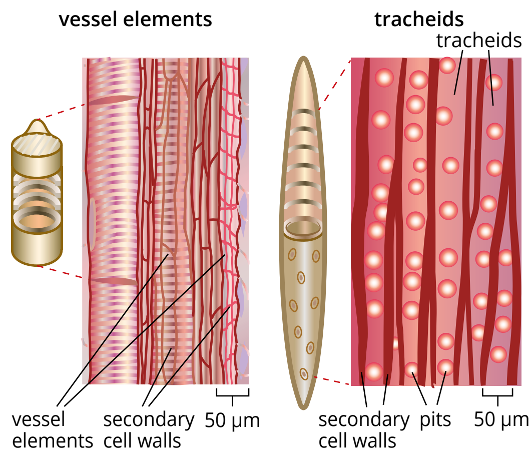


FIGURE 6.1.3 Water and mineral ions travel through vessels and tracheids in the xylem tissue. This figure shows the different forms of individual xylem elements. Xylem vessel elements are joined end to end to form a long tube, while tracheids exist singly and are connected through pits along their cell walls.

Tracheids

Tracheids are single, large, tapering water-filled cells that form part of the xylem tissue in all vascular plants (Figure 6.1.3). When mature, tracheids lose their nucleus and cytoplasm. This leads to cell death, but creates an open structure for water to flow through. Mature tracheids have:

- cylindrical skeletons of dead cells joined to form continuous tubes, like xylem vessels
- pits and perforations in their lignified cell walls
- no nucleus or cytoplasm.

Unlike xylem vessels, tracheids are not connected end to end. Instead, their ends overlap and water is transferred horizontally through the adjoining pits.

Root absorption

The major function of roots is to take in water and mineral ions from the soil. Water is essential for photosynthesis, nutrient transfer and **transpiration**, while mineral ions (e.g. nitrogen, phosphorus and potassium) are needed to manufacture a range of organic compounds, including amino acids, proteins and lipids.

Roots have a branched structure that increases both their surface area and their capacity to absorb water and mineral ions (Figure 6.1.4).

FIGURE 6.1.4 A branched root structure increases the surface area over which a plant can absorb water and nutrients from the soil.

Water pathways

There are two possible pathways for movement of water and mineral ions absorbed from the soil via the roots: the extracellular pathway and the cytoplasmic pathway (Figure 6.1.5).

In the extracellular pathway, most water and some mineral ions pass in or between cell walls. In the cytoplasmic pathway, most mineral ions and some water pass through the cytoplasm of living root cells. The cytoplasmic pathway involves substances entering a root hair cell by crossing the cell's membrane, and then passing from cell to cell through **plasmodesmata**, which are strands of cytoplasm that connect one cell with the next.

There are three types of transport that move substances across cell membranes and along the cytoplasmic pathway: **active transport**, **osmosis** and **diffusion**. You learnt about these processes in Chapter 3.

GO TO ➤ Section 3.1 page 112

- Active transport—most dissolved mineral ions are selectively taken into roots by active transport. Proteins in the cell membrane of root cells, specific for each ion, are used for this purpose. As a result, the concentration of ions in the vascular tissue of roots can be more than 100 times their concentration in the water of the surrounding soil.
- Osmosis—the high concentration of ions in the vascular tissues of terrestrial plants creates a very large osmotic concentration gradient. Large amounts of water move into root cells along this concentration gradient.
- Diffusion—some mineral ions, such as potassium and phosphate, enter the roots by diffusion. The uptake of these nutrients therefore depends on the rate of water uptake.

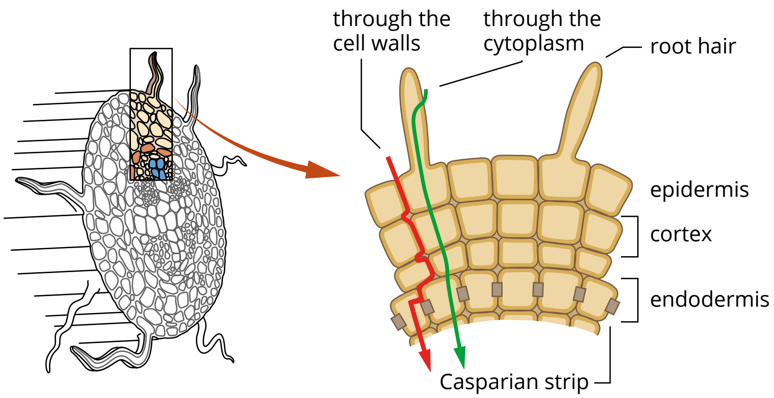


FIGURE 6.1.5 Water and mineral ions move through the roots via the extracellular pathway (red arrow) and the cytoplasmic pathway (green arrow). From the row of cells called the Casparian strip, water can no longer travel along the extracellular pathway and is forced into the cytoplasm before moving into the xylem.

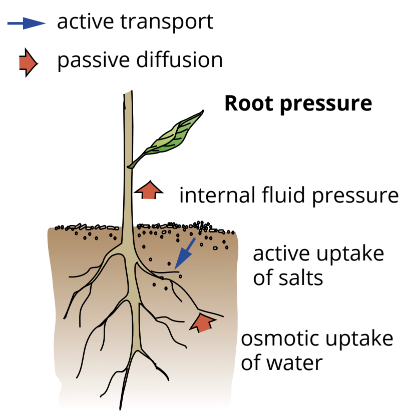


FIGURE 6.1.6 Internal fluid pressure (root pressure) in the roots of some plants causes fluid to rise through the xylem vessels.

Root pressure

In some plants, the osmotic gradient draws in so much water from the roots that it can travel up to 10 m up the stem. This is known as **root pressure** (Figure 6.1.6). In some deciduous trees, such as birch trees, root pressure causes the rising of sap (water and mineral ions) in spring when the soil is warm and rainfall is high.

In some small plants, root pressure also results in a process called guttation. This is the loss of liquid water, and sometimes other substances, from leaves—unlike transpiration, which is the loss of pure water in the form of water vapour. In **guttation**, water is lost through specialised pores at the ends of leaf veins (Figure 6.1.7).

FIGURE 6.1.7 Root pressure in small plants can force droplets of water from specialised pores at the tips of leaf veins, a process called guttation.

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Water transport adaptations in desert plants

Plants that live in deserts need strategies to survive the hot, dry conditions (Figure 6.1.8). In an environment where water is scarce, plants have developed structures that enable extremely efficient uptake and storage of this precious resource.

Cactus plants can hold large volumes of water in their fleshy leaves, stems and roots. When water is available, they need to be able to absorb as much as they can, as fast as they can. Their roots are shallow and cover a large area, enabling them to harvest as much water from the soil as possible.

Once cacti have water, they need to hold on to it. Most cacti are spiny, bitter tasting or toxic, which deters thirsty animals. A thick, waxy cuticle also protects the leaves from damage and reduces water evaporation. While most plants open their stomata during the day, in a hot, dry environment this would lead to massive water loss through transpiration. To overcome this problem, cacti open their stomata at night.

At night, when stomata are open, carbon dioxide is taken in and converted to malic acid. The malic acid is stored in the vacuoles of mesophyll cells. In daylight, when the stomata stay closed to reduce water loss, the stored malic acid is broken down. This releases carbon dioxide, which diffuses into chloroplasts for conversion into glucose and carbohydrates, completing the photosynthetic process. A type of photosynthesis called CAM photosynthesis is excellent for conserving water, but the rate of photosynthesis is slow. As a result, many cacti grow very slowly.

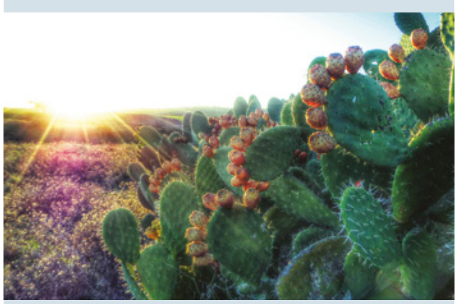

FIGURE 6.1.8 Cacti have many adaptations to overcome the problem of water uptake and storage in harsh, dry environments.

It usually occurs at night when the air is moist. In tropical conditions, where humidity in the surrounding air is so high that little transpiration occurs, guttation helps plants survive by ensuring the continual upward movement of sap, which transports essential mineral ions from the soil to the leaves.

Entering the xylem

From either of the two pathways through the roots (the extracellular pathway or the cytoplasmic pathway), water and mineral ions must then reach the xylem tissue. Between the roots and the xylem is a waterproof layer of cells that form a barrier known as the **Casparian strip** (Figure 6.1.5). At this barrier, water travelling through the extracellular pathway is forced into the cytoplasm. In this way, the Casparian strip regulates the substances entering the xylem.

TRANSLOCATION OF SUGARS

Plants transport water, gases and minerals from their roots to the aerial parts of the plant. The transport of **organic solutes** from the leaves to other tissues in the plant is known as **translocation**. Leaves produce carbohydrates in the form of sugars during photosynthesis. The non-photosynthetic tissues of the plant also need these carbohydrates—and other organic compounds, such as amino acids, hormones and proteins—so these nutrients are transported from the leaves to where they are needed, e.g. roots, bulbs, stems, flowers and fruits.

Phloem

The tissue through which organic solutes move is the phloem, and the material that flows through it is known as phloem sap.

Phloem transports organic solutes, such as sugars and amino acids, from the leaves (site of photosynthesis) to the stems and roots (site of use or storage). The plant uses or stores the sugars in its cells to produce energy for growth and reproduction. Plants can store sugar in their cells as **starch**. Starch can be used for structural support, or as an energy source when the plant cannot photosynthesise. Examples of storage structures are bulbs, such as onions, or tubers, such as potatoes.

Phloem tissue is composed of:

- sieve tubes
- companion cells
- parenchyma cells
- sclerenchyma cells.

Sieve tubes

Unlike xylem vessels, mature phloem **sieve tubes** are living cells with no nucleus and no lignin in the cell walls. Sieve tubes form linear rows of elongated cells. Their cell walls are thin and perforated at each end by holes or pores, forming sieve plates (Figure 6.1.9). Plasmodesmata pass through the perforations in sieve tubes, acting like straws through which sugars and other materials can move.

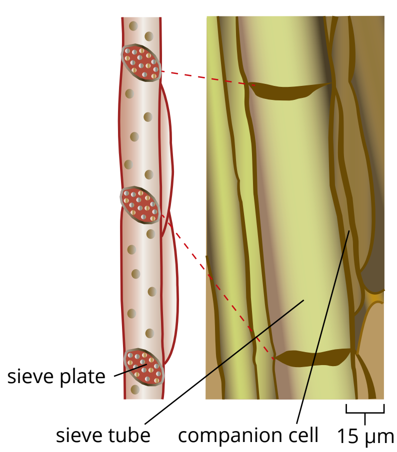

FIGURE 6.1.9 The cytoplasm of sieve tubes in phloem is continuous from cell to cell through the sieve plates. Sieve tube cells don't have a nucleus, but can continue functioning because they are connected via strands of cytoplasm (plasmodesmata) to adjacent companion cells with nuclei.

Sieve tube cells are usually closely associated with one or more **companion cells**, connected by plasmodesmata. Sieve cells are able to continue functioning without a nucleus because of their close relationship with companion cells.

Companion cells

Companion cells are a type of **parenchyma** cell that provide metabolic support and help load and unload materials throughout the plant. Like sieve tube cells, companion cells have thin cell walls. Companion cells retain their nuclei and carry out all the metabolic functions required by the sieve tube cells, sharing metabolic products through the plasmodesmata. Without the metabolic products from the companion cells, sieve tube cells would die, preventing the flow of phloem sap and killing the plant.

Parenchyma cells

Parenchyma cells make up the soft tissue of a plant and have many important functions. In leaves, they contain chloroplasts and make up the mesophyll—the inner layer of a leaf where photosynthesis takes place. Parenchyma cells that contain chloroplasts are called **chlorenchyma** cells.

In roots and tubers (e.g. potatoes), parenchyma cells have large vacuoles that store starch, fats, proteins and water. Parenchyma cells also provide buoyancy in aquatic plants and play a role in wound repair. Because of the different functions of parenchyma cells, their structure varies from elongated to spherical.

Sclerenchyma cells

Sclerenchyma cells provide strength and structural support for the plant. Mature sclerenchyma cells are dead and have very thick cell walls made of cellulose and lignin. There are two types of sclerenchyma cells: fibres and sclereids. Fibres are found in stems, roots and the vascular tissue of leaves. Sclereids are found in the outer layer of seeds and the shell of nuts. The fibres of some plants, such as flax and hemp, have important uses as textiles.

Translocation: sources and sinks

The sites where sugars are produced during photosynthesis are known as **sources**. The sources in a plant are the leaves. The sugars produced during photosynthesis need to be translocated to non-photosynthetic (food-producing) cells throughout the plant. The sites where sugars are translocated to are known as **sinks**. The sinks in a plant include the roots, bulbs, stems, flowers and fruits.

The sugars are translocated in phloem sap, which is around 90% sucrose. Sucrose is a disaccharide that dissolves easily in water, making it a good transport material. Glucose (a monosaccharide) is produced in the chloroplasts of the chlorenchyma cells and converted to sucrose in the cytosol of cells. Sucrose is then pumped into the companion cells and from there, flows into the sieve tube cells (Figure 6.1.10).

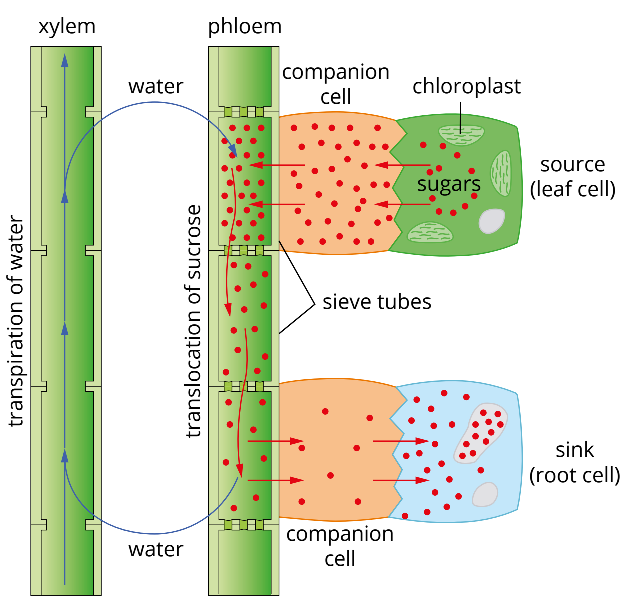

FIGURE 6.1.10 The movement of fluid through the phloem is the result of active pumping of sugars, with water flowing along an osmotic gradient. Sugars and water enter the phloem sieve tubes in leaves and are translocated throughout the plant. Sugars are actively unloaded from sieve tubes where required.

Sieve tube cells have no nuclei and reduced numbers of organelles to maximise space for the translocation of materials. Sieve tube cells also have thick and rigid cell walls to withstand **hydrostatic pressure**, which assists the flow of solutes. Transport in individual sieve tube cells is in one direction only, but bundles of sieve tube cells transport sap in both directions: upwards to leaves and fruit, and downwards to the roots.

Translocation is an active process. It involves the flow of cytoplasm in sieve tubes driven by a pressure gradient, and requires the expenditure of energy by the plant. The pressure gradient begins in the leaves, where sucrose is actively pumped into phloem sieve tube cells. Due to the incompressibility of water, the build-up of water in the phloem creates an osmotic gradient that draws water passively into the sieve cells. As water enters, it increases the fluid pressure (turgor) in sieve cells, which pushes fluid into the adjacent sieve cells.

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While this is happening in the leaves, sucrose is being actively removed from sieve cells in roots, and used for growing shoots and developing fruit. This causes an osmotic gradient that draws water out of sieve cells and lowers their turgor pressure.

Fluid pressure is therefore high in sieve tube cells in leaves, and low in sieve tube cells in roots and growing shoots. Most of the phloem sap in sieve tubes flows along this fluid pressure gradient from sources to sinks. This allows the phloem to translocate solutes away from the source and towards the sink. Translocation stops if the cells in the stem die.

BIOLOGY IN ACTION CCT

The Separation Tree

On 15 November 1850, citizens gathered under the canopy of a majestic river red gum (*Eucalyptus camaldulensis*) in the newly established Royal Botanic Gardens in Melbourne. Superintendent Charles La Trobe announced that Victoria would separate from New South Wales and become a new colony of the United Kingdom. The tree was commemorated with a plaque and named the Separation Tree. The tree is now heritage listed and is believed to be over 400 years old.

FIGURE 6.1.11 The Separation Tree following the first vandalism attack in 2010

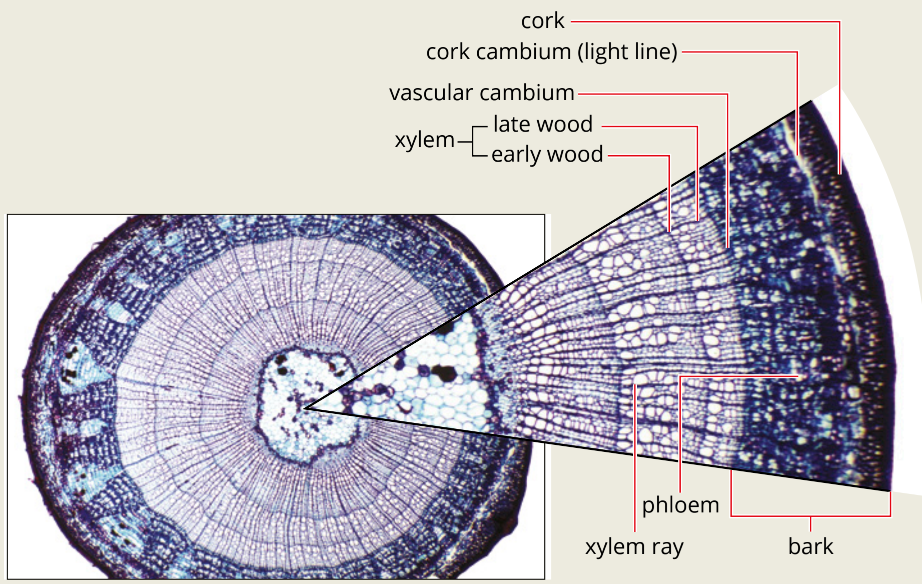

FIGURE 6.1.12 Cross-section of the woody stem of a three-year-old *Tilia* tree, showing the different tissues that contribute to healthy functioning. The pith is at the centre, surrounded by three annual rings and the bark, which is the outer portion of the stem. Removing the bark by ring barking cuts off tissues essential for the transport of vital water and nutrients between the leaves, stem and roots of the plant.

Sadly, the Separation Tree was attacked in 2010 and 2013 by vandals, who removed deep strips of bark from the trunk (Figure 6.1.11). This is known as ring barking or girdling, and involves removing a strip of bark from the whole circumference of the trunk. The bark that is removed contains the cork cambium, phloem tissue, vascular cambium and sometimes the xylem tissue (Figure 6.1.12).

Although the leaves of the Separation Tree were still able to photosynthesise and produce sugars, the sugars could no longer be transported to the roots, and the roots starved. Despite efforts to save the tree, it was confirmed as dying in February 2015. For safety reasons, the branches and upper trunk of the Separation Tree have now been removed.

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Transport in 'non-vascular' plants

Bryophytes (mosses, liverworts and hornworts) are often called non-vascular plants, because they do not have a system like that in vascular plants for transporting fluids. Most species can take in nutrients and water directly into their cells by diffusion.

However, many bryophyte species have an internal transport system for conducting fluids, so 'non-vascular' is not really the correct term. One major difference between bryophytes and vascular plants is that the cell walls of bryophytes do not contain lignin, which gives extra strength to the wall and enables plants to grow much taller. Non-vascular plants should be called 'non-lignified' plants.

The transport system in bryophytes consists of long cells called hydroids, which are bundled together to form a tissue called the hydrome. Some species have a lignin-like substance in the cell walls of hydrome cells, giving them more rigidity. One of these is the largest non-vascular plant in the world: the giant dawsonia (*Dawsonia superba*) (Figure 6.1.13). It is a moss that grows in wet forests and rainforests in Australia and New Zealand, and reaches 65 cm in height—taller than many vascular plants.

FIGURE 6.1.13 The giant dawsonia (*Dawsonia superba*) is one of the largest non-vascular plants in the world. It has an internal transport system and is taller than many vascular plants.

TRANSPIRATION

Transpiration is the passive movement of water through the xylem of vascular plants, from the roots to the leaves (Figure 6.1.14). Transpiration also includes the evaporation of water from the leaves via the stomatal pores. The plant uses a small amount of water for metabolic processes, but 99% of the water absorbed by the roots is lost via transpiration.

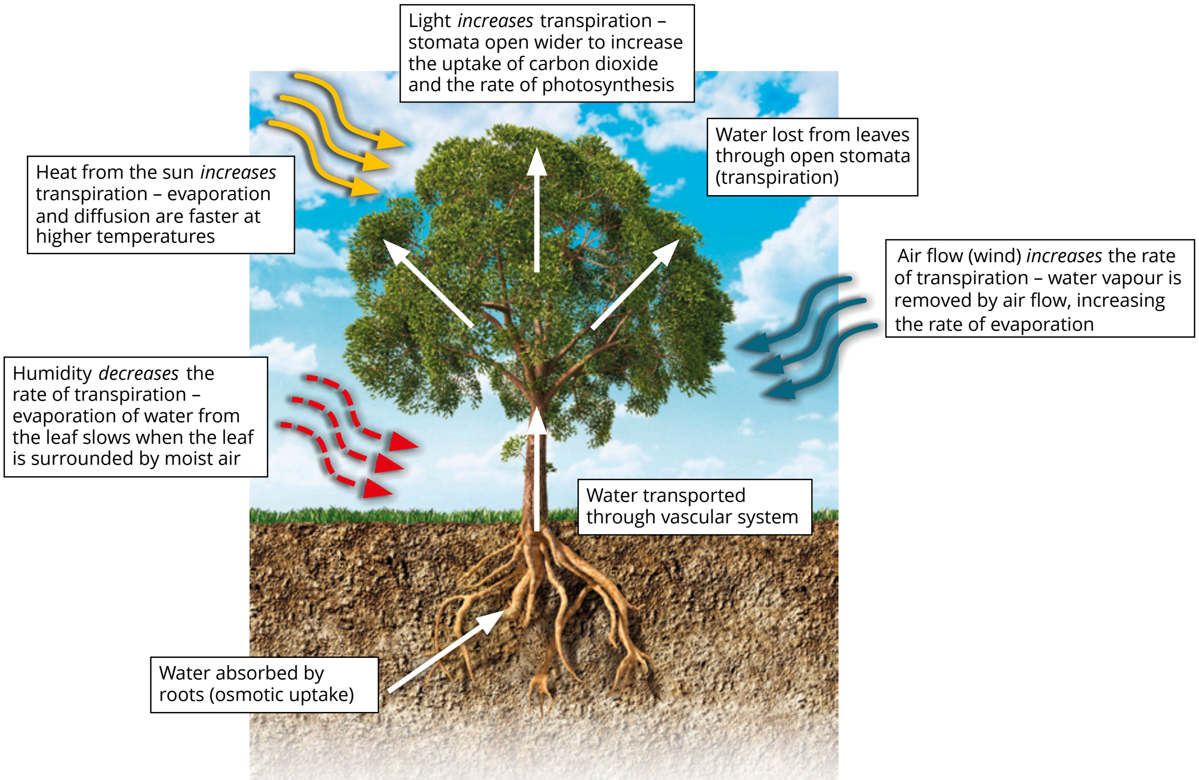

FIGURE 6.1.14 Transpiration is the movement of water through the xylem vessels of vascular plants and into the atmosphere through leaf stomata in the form of water vapour. Environmental factors, such as sunlight and humidity, affect the rate of transpiration and therefore the rate of water uptake by the roots.

Although most of a plant's water is lost via transpiration, it is a vital process because it enables plants to:

- absorb the water necessary for photosynthesis
- transport mineral salts to leaf cells and fruits
- cool down and not become overheated.

Transpiration is a passive process: it does not require energy expenditure by the plant. It is driven by the heat energy in sunlight, which breaks the cohesive bonds between water molecules, allowing evaporation through the stomata.

Transpiration–cohesion–tension theory

Although transpiration is a passive process, it requires the movement of water against the force of gravity. The **transpiration–cohesion–tension theory** was first proposed in 1894 by John Joly and Henry Horatio Dixon and is now the most widely accepted theory to explain the upwards movement of water through the xylem of plants. The theory explains the primary mechanisms of water movement in plants: **cohesion** between water molecules, **adhesion** between water molecules and plant cell walls, and the tension (differential pressure) created when water evaporates from the leaves.

Water molecules are very cohesive—they have a strong tendency to stick together. Water molecules are also adhesive, meaning they have a tendency to stick to other molecules. The adhesive quality of water allows it to stick to the hydrophilic cell walls in the xylem of the plant. It is the cohesion and adhesion of water molecules that allows water to move against the force of gravity.

The flow of the transpiration stream does not require an intact root system. It continues when cut flowers and leafy shoots are placed in a vase of water. It also continues in the roots after the stem dies.

Because of cohesion, water molecules evaporating from the surface of a leaf pull adjacent water molecules with them. Water in nearby xylem vessels is then drawn up to the leaves to replace the water lost via evaporation. In this way, thousands of leaf cells, each drawing water from the xylem, create tension (differential pressure) that pulls water up the xylem vessels from the roots.

This continuous one-way flow of water from roots to leaves is called the **transpiration stream**. The pull of transpiration can be strong enough to draw water to the top of the tallest tree, more than 100 m high.

Factors affecting transpiration rates

Water vapour is lost from leaves by transpiration through open stomata. The total surface area across which transpiration takes place is related to the degree of opening of all stomata. This is by far the most important factor affecting the rate of transpiration. The greater the number of stomata and more open they are, the more surface area there is from which water can be lost (Figure 6.1.15). The rate of transpiration is higher during the day than at night because stomata open during the day to exchange gases during photosynthesis, and close at night to minimise water loss.

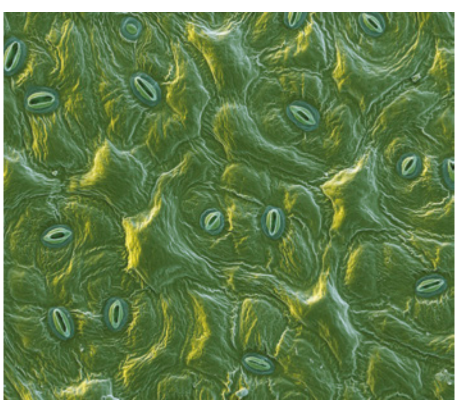

FIGURE 6.1.15 Stomata on the surface of a cabbage leaf, viewed at high magnification. Stomata play an important role in transpiration, because they regulate the exchange of gas and water between the plant and the atmosphere.

Other factors that affect the rate of transpiration include:

- humidity—transpiration rates decrease when there is a lot of water vapour in the air (i.e. a high level of humidity). Humidity reduces the water concentration gradient between leaf spaces and air, so fewer water molecules evaporate into the air.
- temperature—transpiration rates increase as temperature increases, because heat energy increases the rate of water evaporation.
- wind—air currents increase the rate of transpiration by moving water vapour away from the leaf and increasing the rate of evaporation of water.

The leaves of some plants that live in exposed conditions have developed structural features that reduce the rate of transpiration. For example, some plants have hairs on the leaf surface, which create a layer of relatively undisturbed, humid air.

6.1 Review

SUMMARY

- Most terrestrial plants, including ferns, conifers and flowering plants, have specialised vascular tissues (xylem and phloem) that transport fluid.
- The vascular tissues are:
  - xylem, which carries water and mineral ions from roots to leaves
  - phloem, which carries sugars and other organic molecules from leaves to roots.
- Xylem vessels:
  - are the skeletons of dead elongated cells
  - have perforations at each end
  - are joined end to end to form continuous tubes and allow the flow of fluid
  - have pits (thinner areas) in the side walls that enable the movement of substances into and out of adjacent companion cells.
- Xylem tracheids:
  - are dead, have pits in their lignified cell walls, and have no nucleus or cytoplasm
  - are not connected end to end; their ends overlap and water is transferred horizontally through the adjoining pits.
- Water and inorganic nutrients (mineral ions) are absorbed by the root hairs from the soil by one of two pathways:
  - extracellular pathway
  - cytoplasmic pathway.
- Water and mineral ions are transported through xylem vessels. This transportation occurs in one direction only: from roots to leaves.
- Translocation is the transport of organic materials from the leaves to the roots, stem, flowers and fruits of the plant, through the sieve tube cells and companion cells of the phloem tissue.
- Translocation is an active process and requires an expenditure of energy by the plant.
- Translocation is driven by a pressure gradient that begins in leaves (sources), where sucrose is actively pumped into phloem sieve cells while being actively removed from sieve cells in roots, growing shoots and developing fruit (sinks).
- Transpiration is the evaporation of water from stomata in leaves. It is a passive process (driven by energy from sunlight) that also draws water up from the roots, through the xylem, following what is known as the transpiration stream.
- The transpiration–cohesion–tension theory explains how water moves upwards (against the force of gravity) in plants: cohesion between water molecules, adhesion between water molecules and plant cell walls, and the tension (differential pressure) created when water evaporates from the leaves, draw water upwards through the plant.
- The rate of transpiration is affected by:
  - the number of stomata and their degree of opening
  - temperature
  - humidity
  - wind.
- Organisms must exchange oxygen and carbon dioxide with their environment to maintain cellular respiration and photosynthesis.
- Gas exchange in plants can be measured by analysing the exchange of gases between internal and external environments.

KEY QUESTIONS

1 What are the two types of vascular tissue in plants? State the function of each.

2 Why is there a limit to the size non-vascular plants can grow?

3 How does ring barking affect translocation? What impact does this have on the health of a tree?

4 What are the two possible pathways through the roots for the movement of water and mineral ions absorbed from the soil?

5 How is it possible for the tallest trees to transport water from their roots to their uppermost branches, sometimes more than 100 m high?

6 Why is transpiration vital to plants?

7 According to the transpiration–cohesion–tension theory, what are three factors that explain how water moves against the force of gravity during transpiration?

8 State whether each of the following environmental factors increases or decreases transpiration rates in plants:

a high temperature
b high humidity
c darkness
d strong wind.

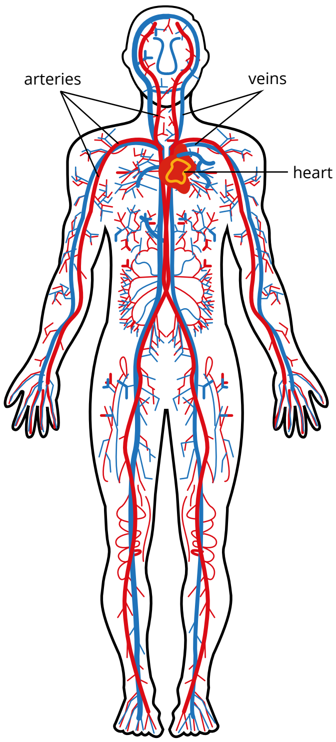

FIGURE 6.2.1 The cardiovascular system is the main transport system in mammals. It is composed of the heart, blood and blood vessels, and is responsible for transporting dissolved gases, nutrients and waste products.

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A system is a group of organs working together to perform one or more functions that contribute to the survival, growth and reproduction of the organism. Like specialised cells, tissues and organs, systems must work together. For example, the cardiovascular system interconnects with all other systems of the human body. Three of these are the digestive system (nutrient absorption), respiratory system (gas exchange) and excretory system (waste removal).

6.2 Transport systems in animals

Mammals, including humans, are composed of billions or even trillions of specialised cells organised into tissues, organs and systems. There are many advantages to this level of complexity. But, as with vascular plants, there are also challenges. For example, specialised cells cannot survive independently and must rely on other cells and the survival of the whole organism. This section examines the cardiovascular and lymphatic mammalian systems, how these systems interconnect, and the consequences for the organism when a system malfunctions.

DISTRIBUTING MATERIALS: MAMMALIAN TRANSPORT SYSTEMS

The structure and function of transport systems are similar in all mammals. Mammals have two transport systems: the **cardiovascular system** (also known as the circulatory system) and the **lymphatic system**.

The cardiovascular system:

- is a **closed circulatory system**
- uses **blood** as the circulatory fluid
- provides most of the transport needs in mammals.

The lymphatic system:

- is an **open circulatory system**
- circulates colourless **lymph** fluid
- plays vital roles in maintaining osmotic and fluid balance in tissues and supporting immune defences.

THE CARDIOVASCULAR SYSTEM

In simple multicellular organisms, nutrients are transported by diffusion between cells . You learnt about diffusion in Chapter 3.

Diffusion only works over short distances from cell to cell. In large, complex animals, diffusion is not sufficient to deliver essential nutrients to every cell. In humans, it would take more than a year for oxygen to diffuse from the lungs to the brain: but the brain cannot function if it is deprived of oxygen for more than about 6 minutes. For this reason, specialised circulatory systems with networks of pipes and chambers have evolved to transport vital nutrients to all cells in complex multicellular organisms. The cardiovascular system delivers oxygen from the lungs to the brain in less than 4 seconds—the time it takes for the heart to beat four or five times.

The mammalian cardiovascular system (Figure 6.2.1) is a closed system that transports substances throughout the body. The vital metabolic products of the body are transported via the blood. The blood, circulatory tissues and organs ensure that all cells have a ready supply of nutrients and oxygen and a means to transport away metabolic wastes. In mammals, the highly branched network of the cardiovascular system means that no cell is more than 1 mm from a capillary. This ensures efficient nourishment and waste removal for all cells in the body.

Circulation pathways

Blood circulates around the body via two sequential pathways (Figure 6.2.2):

- **Pulmonary circulation** transports blood to and from the lungs. Deoxygenated blood is pumped from the heart to the lungs, where it is oxygenated before returning to the heart.
- **Systemic circulation** transports blood to and from the rest of the body. This system is larger than the pulmonary circulatory system, because the heart must pump blood to all the organs in the body. Oxygenated blood is pumped from the heart to the organs, where it gives up its oxygen to the cells before returning to the heart.

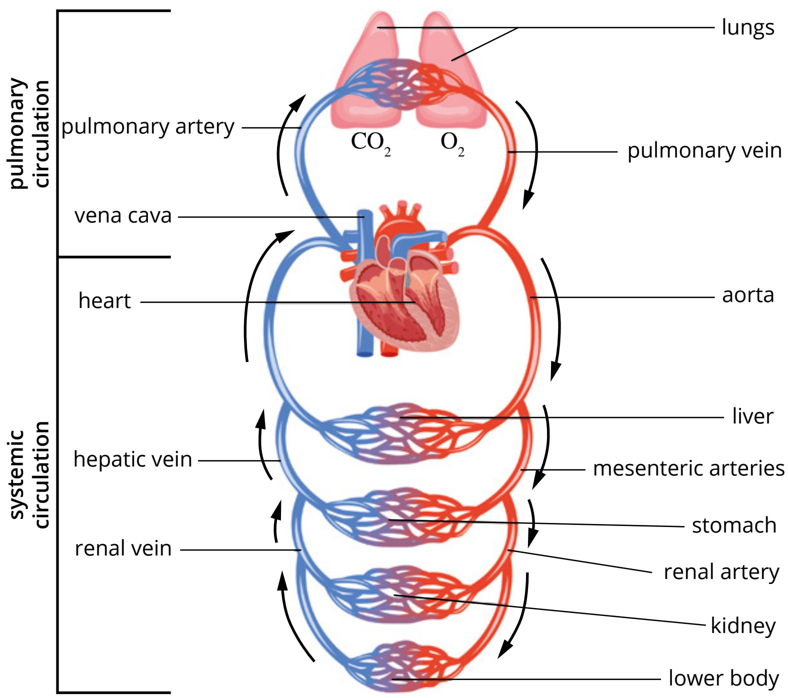

FIGURE 6.2.2 Pulmonary circulation transports blood to and from the lungs. Systemic circulation transports blood to and from all the systems in the mammalian body.

Components of the cardiovascular system

The key components of the cardiovascular system are the **heart**, **blood vessels** and blood.

The human heart is a four-chambered muscular pump with two pumping chambers (ventricles) and two receiving chambers (atria). It is responsible for moving blood throughout the cardiovascular system. The right side of the heart pumps **deoxygenated blood** (blood with a low oxygen concentration), while the left side pumps **oxygenated blood** (blood with a high oxygen concentration).

Blood vessels are a network of muscular vessels carrying blood to and from the heart. They are divided into:

- pulmonary vessels, which carry blood to and from the lungs
- systemic vessels, which carry blood to and from all other parts of the body.

There are three types of blood vessels: **arteries**, **veins** and **capillaries**.

- Arteries carry blood away from the heart. They have thick, muscular walls and carry blood under high pressure.
- Veins carry blood to the heart. They have thin walls and carry blood under low pressure.
- Capillaries connect the arteries and veins. Capillaries are fine vessels with very thin walls (one cell thick) that carry blood under low pressure. The thin walls of capillaries allow gases and nutrients to pass between the capillaries and tissues.

Blood is the circulating fluid and is highly specialised for transport and immune defence.

The heart

The mammalian heart is in the centre of the chest, between the lungs, surrounded by the protective rib cage. It has several tissues, including cardiac muscle (Figure 6.2.3), **connective tissue** and nerve tissue. Connective tissue makes up the **valves**, while nerve tissue controls the heart rate. A mammalian heart can keep beating even if it is separated from the body, because it has its own electrical impulses.

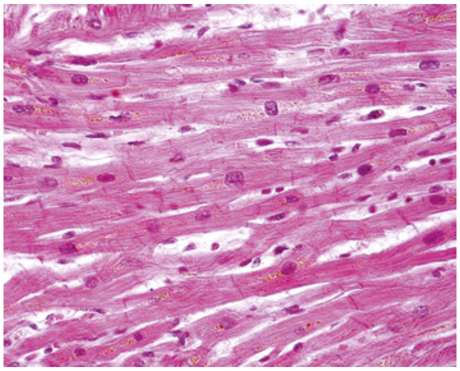

FIGURE 6.2.3 Cardiac muscle tissue is made of highly specialised muscle cells that are found only in the heart. The dark bodies are nuclei.

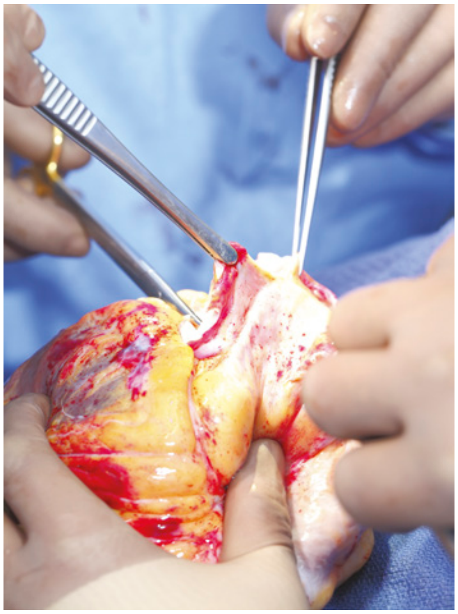

FIGURE 6.2.4 A human heart being prepared for transplant

This property can be used in a type of heart transplant called a 'living organ transplant', where a still-beating heart is transplanted into a patient (Figure 6.2.4).

The mammalian heart has four chambers (Figure 6.2.5). The upper receiving chambers, which have thinner walls, are the atria (singular **atrium**). Each atrium opens into one of the lower, thicker-walled chambers, called **ventricles**. Blood moves through the heart in one direction because of the presence of four one-way valves: one between each atrium and the ventricle below, and one between each ventricle and its outgoing artery.

Both sides of the heart function in a coordinated way: first both atria contract, then both ventricles contract. The right side of the heart pumps deoxygenated blood to the lungs, where it becomes oxygenated. The left side of the heart pumps oxygenated blood from the lungs around the body (Figure 6.2.5).

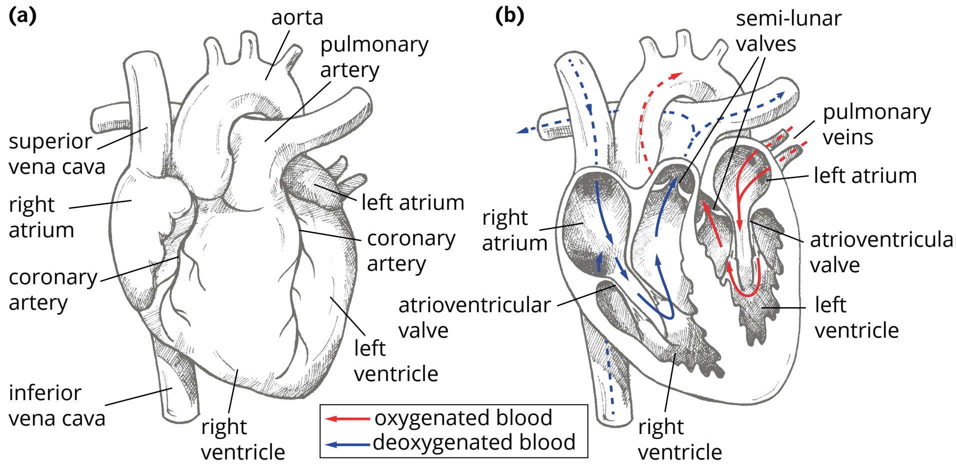

FIGURE 6.2.5 The human heart. (a) View of the ventral surface of the heart, and (b) ventral surface opened to show the major vessels, valves and the greater thickness of the left ventricle wall

Blood flow through the heart

When the heart beats, it pushes blood through its chambers in a specific sequence. This ensures that deoxygenated blood is transported to the lungs, while oxygenated blood is transported to the rest of the body. One complete circuit through the cardiovascular system of the human body takes about 45 seconds.

Blood flows through the heart and body in the following sequence:

Right side of the heart:

- Deoxygenated blood, returning from the body, enters the heart through two large veins (the inferior vena cava and the superior vena cava).
- The deoxygenated blood flows through the vena cavae into the right atrium.
- As both heart chambers relax between contractions, the deoxygenated blood flows through a valve into the right ventricle.
- The atrium contracts first, pushing more deoxygenated blood into the right ventricle.
- As the ventricle contracts, the rising ventricular pressure closes the valve between the atrium and ventricle (atrioventricular valve) and opens the valve between the ventricles and the opening of the **pulmonary artery** (semilunar valve), pushing blood into the pulmonary artery.
- Blood travels through the pulmonary artery to the lungs where it is oxygenated.

Left side of the heart:

- In the lungs, blood loses carbon dioxide and gains oxygen by diffusion as blood flows through the narrow capillaries around the alveoli.
- Oxygenated blood returns from the lungs to the left atrium through the **pulmonary vein**.
- The oxygenated blood is pumped by the left ventricle to the rest of the body via the **aorta**.

Table 6.2.1 summarises the functions of the main parts of the human heart.

TABLE 6.2.1 The main components of the human heart and their functions

Structure	Type	Function
right atrium	chamber (upper)	receives deoxygenated blood returned from the body
right ventricle	chamber (lower)	receives deoxygenated blood from the right atrium and pumps it to the lungs
left atrium	chamber (upper)	receives oxygenated blood from the lungs
left ventricle	chamber (lower)	receives oxygenated blood from the left atrium and pumps it to the rest of the body
venae cavae	vessels (veins)	deoxygenated blood returns from the body to the right atrium
pulmonary artery	vessel (artery)	deoxygenated blood is pumped by the right ventricle and flows to the lungs
pulmonary veins	vessels (veins)	oxygenated blood returns from the lungs to the left atrium
aorta	vessel (artery)	oxygenated blood is pumped from the left ventricle and flows to the rest of the body

The heart is an active organ

The heart is a continuously active muscular organ, so it has a high requirement for nutrients and oxygen. The cells of the heart have their own rich blood supply via the **coronary circulation**.

The coronary circulation consists of vessels that spread across the surface of the heart and into the heart tissue. They include:

- arteries
- **arterioles**
- capillaries
- **venules**
- veins.

WS 2.8

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Arteries, veins and capillaries

Blood vessels (Figure 6.2.6) are named according to their structure and position in the cardiovascular system.

- Arteries transport blood away from the heart.
- Veins transport blood towards the heart.
- Capillaries are the narrow exchange vessels between arteries and veins.

Arteries and veins are composed of the same layers of tissue, but arteries have more muscular walls, and veins are more easily stretched. Capillaries have very thin walls consisting of only a single layer of flattened epithelial cells.

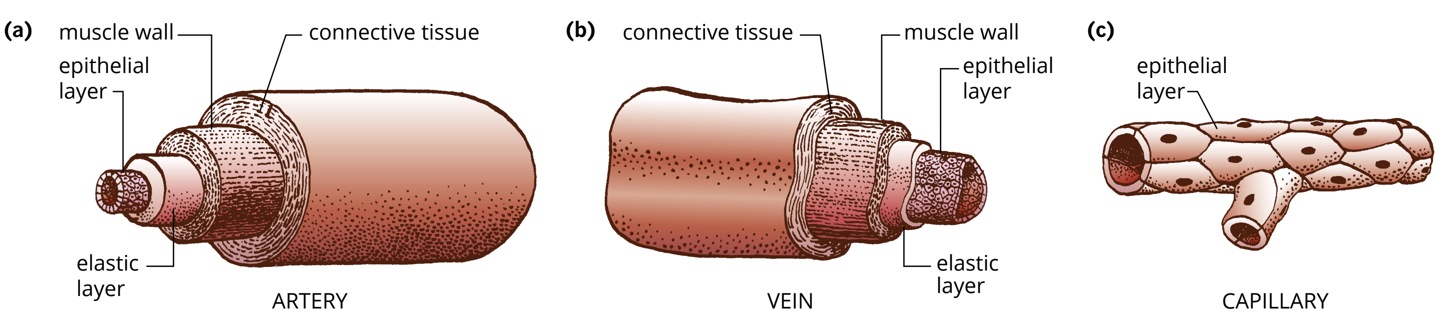


FIGURE 6.2.6 Wall structures of (a) an artery, (b) a vein and (c) a capillary

The structure, function and other features of the blood vessels in the cardiovascular system are summarised in Table 6.2.2.

TABLE 6.2.2 Structure and function of the blood vessels in the cardiovascular system

	Arteries	Veins	Capillaries
Structure	• consist of an epithelial layer of cells, an elastic layer, muscle wall and connective tissue • same structure as veins but thicker muscular walls	• consist of an epithelial layer of cells, an elastic layer, muscle wall and connective tissue • same structure as arteries but thinner muscle walls	• consist of a single layer of flattened epithelial cells • very thin walls
Function	• transport blood away from the heart	• transport blood towards the heart	• connect arteries to veins • deliver nutrients and other substances to extracellular fluids, and receive wastes
Other features	• higher blood pressure than veins	• contain many one-way valves • lower blood pressure than arteries	• very large number • form a network within tissues to be near most cells

Capillaries

Capillaries are the smallest of the blood vessels. Their internal diameter is so small that blood cells must travel through them in single file (Figure 6.2.7). The capillaries:

- connect arteries to veins
- deliver oxygen, nutrients and other substances to extracellular fluids via diffusion
- receive carbon dioxide and other wastes.

Capillary walls are extremely thin—just one epithelial cell thick—and porous, which allows substances to pass in and out of the cardiovascular system. Because of their important role in the transport of oxygen and nutrients to tissues, capillaries are most abundant in metabolically active tissues and organs, such as muscle tissue.

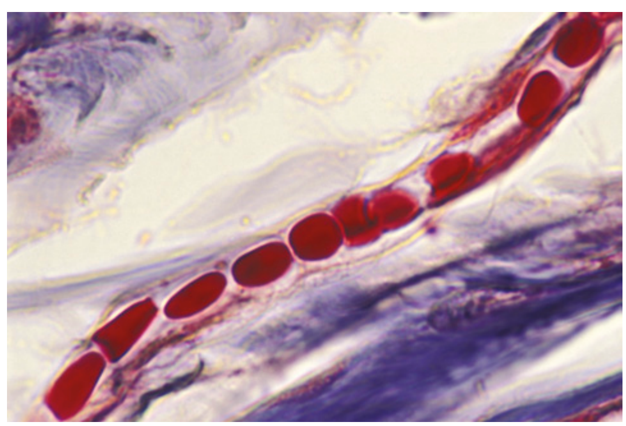


FIGURE 6.2.7 Red blood cells flow in single file through a capillary.

Capillaries are distributed throughout the body as an enormous branched network, providing a vast surface area for the exchange of materials between the blood and extracellular fluid. The total length of blood vessels in an average human body is nearly 100 000 km. Most of this length is capillaries, which provide a total surface area of more than 1000 m^2 for the exchange of nutrients, oxygen, carbon dioxide and wastes between blood and extracellular fluid. The interwoven network of blood vessels is known as a capillary bed.

A capillary has a diameter of 5–10 µm, so **red blood cells** (about 7–10 µm in diameter) pass very close to the capillary walls. When the wall of a red blood cell presses against a capillary wall, there is an exchange of oxygen and carbon dioxide. The flattened shape and lack of a nucleus in red blood cells are believed to improve their transport capability, by increasing the surface area available for exchange. Their membrane structure makes them very flexible, allowing them to fold and squeeze through the narrow capillaries.

Exchange between **blood plasma** and extracellular fluid occurs by diffusion and filtration across capillary walls. To ensure that materials are transported rapidly and efficiently, most cells are no more than 1 mm away from the nearest capillary. Ions and small molecules, such as glucose and amino acids, diffuse through the capillary wall along concentration gradients.

Filtration occurs because of two opposite forces: hydrostatic pressure (or blood pressure) and **osmotic pressure** (Figure 6.2.8). The pressure from these two forces pushes fluid into and out of the capillaries.

- Hydrostatic pressure is a result of blood pushing outwards on the capillary walls.
- Osmotic pressure results from the differing solute concentrations between the blood and the extracellular fluid.

Because blood is hypertonic (more concentrated) than the extracellular fluid, water tries to move through the capillary walls into the blood, putting an inward pressure on the capillaries. The pressure varies along the length of a capillary, but overall the hydrostatic pressure is greater than the osmotic pressure, so more fluid filters out of the capillary than filters in (Figure 6.2.8). This pressure results in a small amount of protein leakage through the capillary wall cells. When blood pressure increases, this leakage is higher and can result in fluid loss to tissues, causing swelling. Reabsorption allows around 85% of the fluid to return to the capillaries, while the remaining 15% enters the lymphatic system.

In some tissues, such as the gut and liver, the capillaries are more permeable and allow large molecules to cross. This helps the absorption of digested foods from the gut, and enables the liver to take in materials to be broken down. In contrast, capillary permeability in the brain is very low, and access of substances to brain tissue is tightly controlled. Nerve tissue is very sensitive to its environment, so it is important that the composition of the extracellular fluid surrounding the brain and spinal cord is carefully regulated.

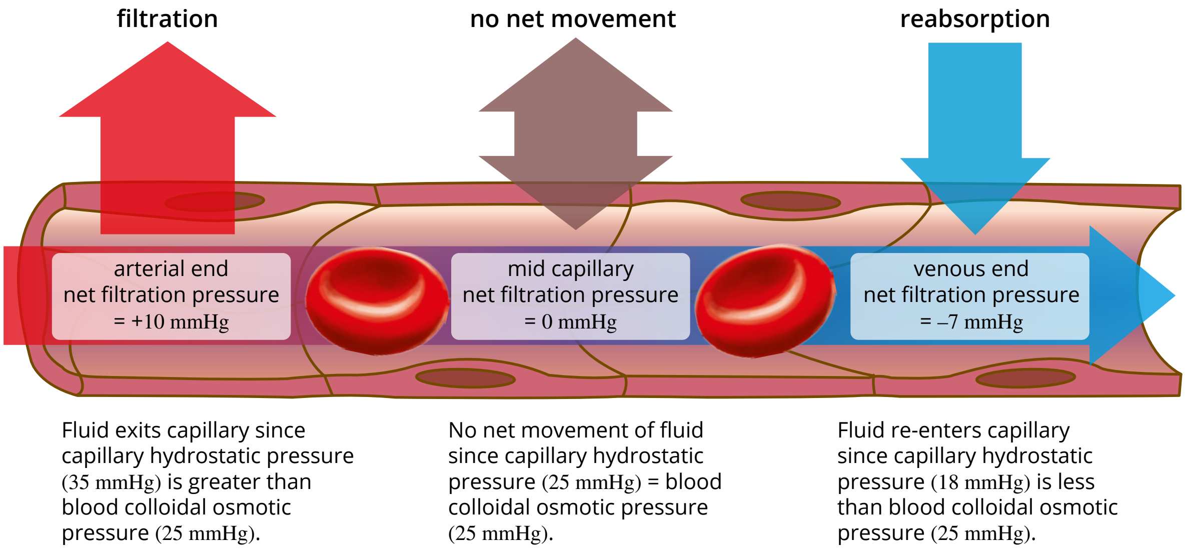


FIGURE 6.2.8 Filtration of fluid across capillary walls is a result of hydrostatic pressure (blood pressure) pushing outwards and osmotic pressure pushing inwards. Overall, hydrostatic pressure is greater and so fluid leaks into the extracellular environment.

Blood vessels can be identified from histological slides or images according to the thickness of their walls:

- Arteries have thick walls composed of three distinct layers (**tunica**).
- Veins have thin walls but typically have wider **lumen** (lumen size may vary depending on the specific artery or vein).
- Capillaries are very small and will not be easily detected under the same magnification as arteries and veins (Figure 6.2.9).

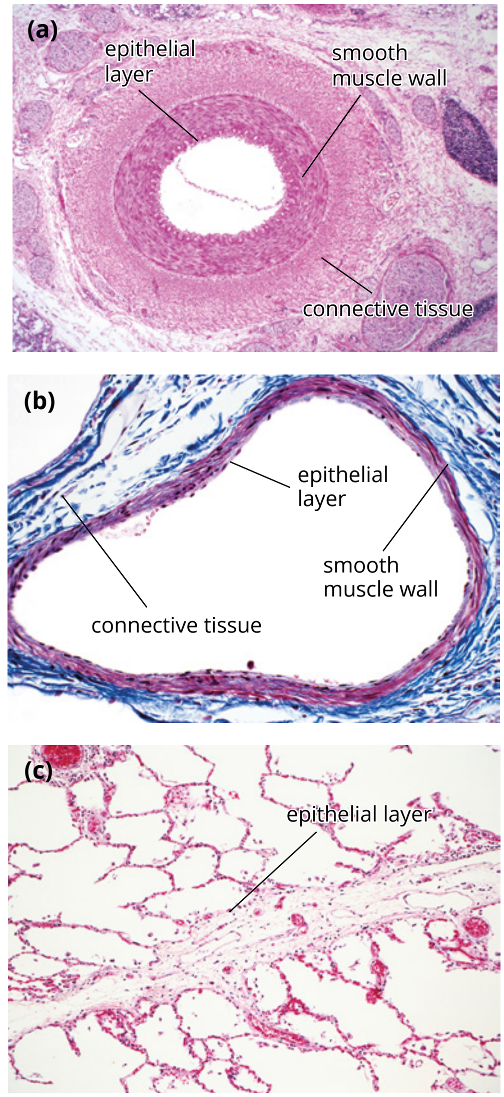


FIGURE 6.2.9 Light micrographs of (a) a cross-section of a human artery, (b) a cross-section through a small, thin-walled human vein, and (c) capillaries. Capillaries are much smaller structures than arteries and veins; image (c) is taken at a high magnification showing a human lung section. The thin alveolar walls have red blood cells in capillaries running through them.

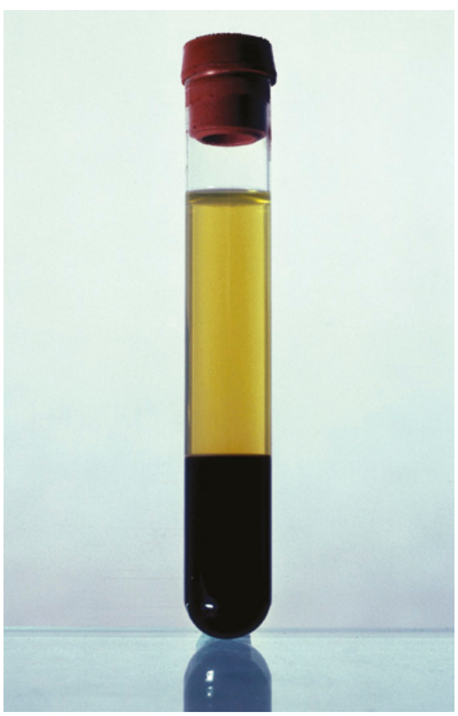


FIGURE 6.2.10 Centrifuged blood separates into plasma (clear, yellow fluid) and the cellular elements (dark red solids).

Blood

Mammalian blood is a fluid containing cells and cellular fragments. The fluid portion of blood is plasma, which is a pale, yellow liquid containing ions, dissolved gases, proteins, hormones, nutrients and wastes. The cellular elements of blood include red blood cells (erythrocytes), **white blood cells** (leukocytes) and **platelets** (thrombocytes) (Figure 6.2.10). They are all produced by cells located in the red bone marrow. The red bone marrow is found in the upper ends of long bones, and in flat bones, such the skull, ribs and pelvis. Blood is a tissue because it is made up of many similar cells working together (Figure 6.2.11).

Red blood cells

Red blood cells make up around 40% of the blood in humans, and a single drop of blood contains about 5 million red blood cells. Mature red blood cells are concave on each side and highly flexible. They lack a nucleus, and are full of the red pigment **haemoglobin**. Unlike carbon dioxide, oxygen is relatively insoluble. Haemoglobin binds to oxygen and transports it to the cells.

Red blood cells live for about 120 days. Old or damaged cells are removed and broken down by the liver or spleen, and important substances, such as iron, are retained and reused by the body. Every second, 2.5 million new red blood cells are released into your bloodstream, and another 2.5 million old red blood cells are removed and destroyed.

White blood cells

White blood cells are slightly larger than red blood cells, but there are far fewer of them (Figure 6.2.11). A drop of blood contains between 5000 and 10 000 white blood cells, but more are held in reserve in organs such as the spleen, kidney, thymus and thyroid gland.

There are several different types of white blood cells. The two most numerous are **phagocytes** (neutrophils) and **lymphocytes**, both of which are involved in defence against microorganisms.

- Phagocytes remove debris and fight infections. They are attracted to a site of infection, where they squeeze through tiny gaps in capillary walls and engulf harmful bacteria and damaged cells.
- Lymphocytes are responsible for the production of antibodies and the development of immune responses.

Platelets

Platelets are fragments of cells. They are much smaller than red and white blood cells, and contain substances that are important in preventing blood loss and promoting blood clotting (see Figure 6.2.11).

Blood pressure

Blood pressure is caused by the contraction of the ventricles. The muscular wall of the left ventricle is almost twice as thick as that of the right ventricle. This is because the left ventricle must pump blood to all the organs, while the right ventricle pumps blood only to the lungs. The right ventricle therefore contracts with less force, resulting in lower blood pressure in the right ventricle and pulmonary arteries than in the more muscular left side of the heart.

In arteries, blood pressure fluctuates with each heartbeat. This produces a pressure wave that can be felt as a pulse where arteries pass close to the surface of the skin, such as at the wrist. The higher **systolic pressure** occurs when the ventricle contracts, and the lower **diastolic pressure** occurs when it relaxes.

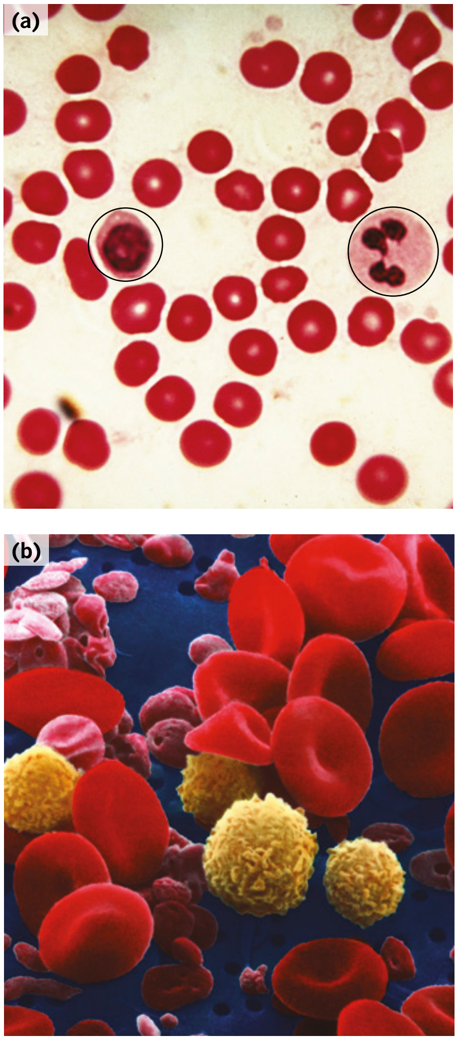


FIGURE 6.2.11 (a) Many red blood cells and two white blood cells (circled) viewed by light microscopy. (b) A coloured scanning electron micrograph (SEM) showing human blood tissue. The red concave discs are red blood cells, the yellow spheres are white blood cells and the smaller pink cells are platelets.

BIOLOGY IN ACTION N PSC

Measuring blood pressure

Normal blood pressure in human adults, which is measured in the large artery of the arm, is about 120/80 mmHg (millimetres of mercury, as measured with an instrument called a sphygmomanometer, which contains a column of mercury. Modern blood pressure meters do not contain mercury). Your doctor might call this ‘120 over 80’. That is, the systolic pressure in the artery of the upper arm is 120 mmHg and the diastolic pressure is 80 mmHg.

Arteries branch to form smaller arteries, called arterioles, which eventually flow into capillaries. As blood flows along the arterioles towards capillaries, blood pressure decreases dramatically. The variation between systolic and diastolic pressure also reduces as blood flows into the smaller arteries, and the difference disappears completely in the capillaries and veins (Figure 6.2.12).

In veins, blood pressure continues to decrease as the blood nears the heart. Blood moves along veins towards the heart as veins are compressed by muscles during body movements. Veins have many one-way valves, so when they are compressed any blood contained in that region will be pushed out in one direction only, towards the heart. This mechanism for returning blood to the heart is particularly important in legs, where blood must flow upwards against gravity.

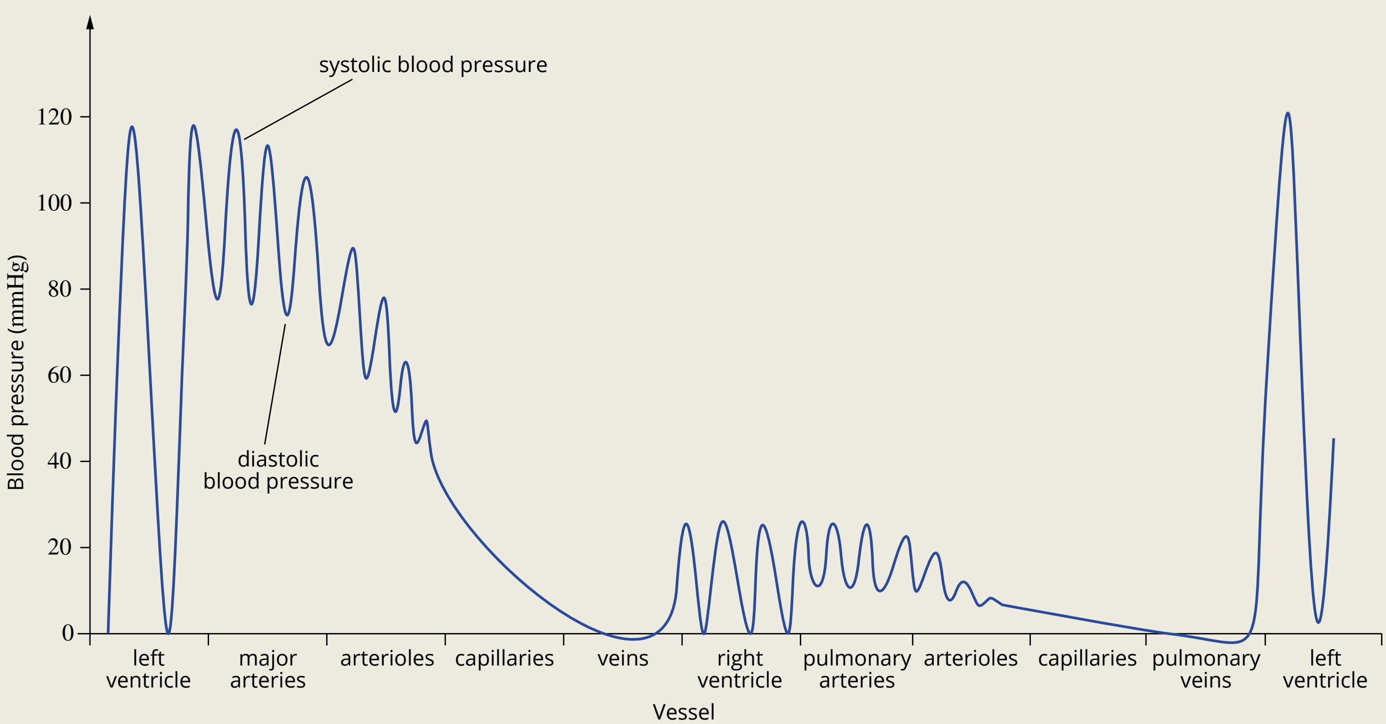


FIGURE 6.2.12 Blood pressure in vessels throughout the human cardiovascular system. Systolic and diastolic pressures fluctuate in arteries and arterioles, and are reduced to almost zero as blood flows through the capillaries. Blood pressure is lower in pulmonary arteries than in systemic arteries. The right ventricle, which pumps blood to the lungs, has a thinner muscle wall and therefore generates a lower pumping pressure than the left ventricle.

BIOFILE ICT PSC

Measuring blood pressure on a smartphone

Blood pressure is measured in arteries using a sphygmomanometer. Arteries are used because veins do not have sufficient pressure to be easily detected.

The sphygmomanometer is a blood pressure cuff that cuts off circulation to a region: typically, the brachial artery in the arm. The pressure of the cuff is slowly released until a pulse can be detected with a stethoscope (systolic pressure). The pressure continues to be released from the cuff until a pulse can no longer be detected (diastolic pressure).

Blood pressure can now be measured using a wireless blood pressure monitor, which transmits data to a smartphone or digital watch (Figure 6.2.13). The ease and speed of digital devices has many benefits. For example, patients using such a device can send data directly to their physician.

FIGURE 6.2.13 A patient demonstrates the Popsicare® wireless blood pressure monitor system. The sphygmomanometer (blood pressure cuff) records blood pressure, heart rate and blood flow, then transmits the data to the patient's smartphone via Bluetooth.

Malfunctions of the cardiovascular system

Problems that can occur when the cardiovascular system malfunctions include Marfan syndrome, arteriosclerosis and atherosclerosis.

Marfan syndrome

Marfan syndrome is an inherited disorder that affects connective tissue. Connective tissue occurs throughout the body, holding together and supporting other tissue (Figure 6.2.14). The cells of connective tissue are held in an extracellular matrix. The extracellular matrix varies in different connective tissues, from hard and tough (e.g. in bone) to jelly-like (e.g. in fatty tissue).

Marfan syndrome is caused by a defective glycoprotein called fibrillin-1. When functioning correctly, fibrillin-1 forms elastic fibres in connective tissue and assists in intercellular communication. When it is defective, the connective tissue tends to be weakened, affecting its function and causing a range of malfunctions in tissues and organs throughout the body.

Weakened connective tissue has the most serious consequences in the heart, lungs, joints, eyes, spinal cord, skeleton and major blood vessels, such as the aorta.

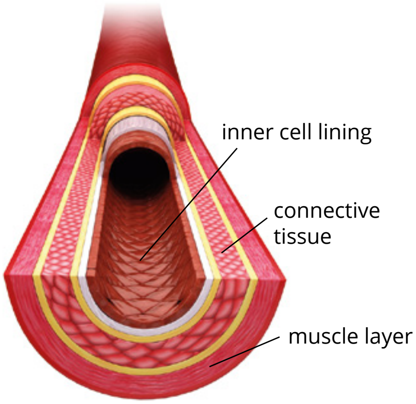


FIGURE 6.2.14 Cross-section of an artery showing the different layers of muscle and connective tissue that support the inner cell lining

The aorta is the largest blood vessel in the body. Blood is pumped from the heart through the aorta to the body under considerable pressure. Weakened connective tissue in the aorta can lead to two major problems:

- The aorta may stretch and bulge under pressure (Figure 6.2.15). This is referred to as an aneurysm. Aneurysms can cause pain, and blood flow may be slowed through the bulge. Slowed blood flow can lead to blood clots, which can break off. They can travel to the brain and cause a stroke, or to the lungs and cause a pulmonary embolism. If the aneurysm ruptures, the patient can die.
- The aorta may begin to tear, so that blood leaks between the layers of the aorta. This can cause pain, lack of blood flow to the tissues and, if left untreated, death.

Both conditions are treatable via surgery if diagnosed early.

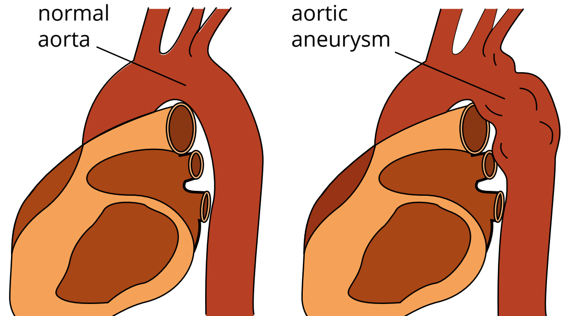


FIGURE 6.2.15 Structure of a healthy aorta compared with an aorta with an aneurysm

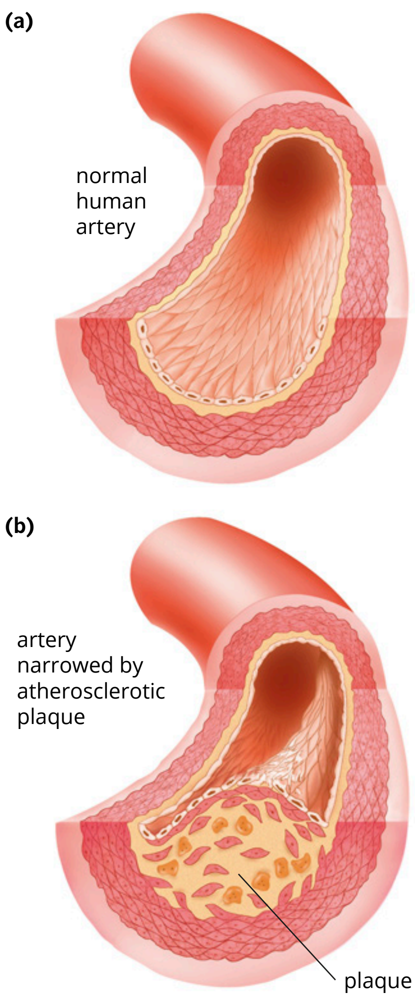


FIGURE 6.2.16 Cross-sections of (a) a normal artery and (b) an artery with atherosclerosis, showing the thickening of the arterial wall caused by a build up of plaque.

Arteriosclerosis and atherosclerosis

With age, the arteries lose collagen and elastin filaments. They gradually become less elastic and begin to harden. This hardening of the arteries is referred to as arteriosclerosis. Arteriosclerosis puts stress on the heart, because it must pump harder to push the blood through the inflexible arteries.

Over time, fatty substances, cholesterol and calcium (together, known as plaque) can build up inside these hardened arteries, causing them to narrow (Figure 6.2.16). This specific type of arteriosclerosis is called atherosclerosis.

Both arteriosclerosis and atherosclerosis can affect arteries and arterioles in all parts of the body and restrict the flow of blood to tissues and organs. If atherosclerosis has developed, plaque can break away or blood clots can form around the plaque. Both these situations can cause a stroke or heart attack.

Atherosclerosis can affect the coronary blood vessels that supply blood to the heart muscle. A build-up of plaque restricts the supply of nutrients and oxygen to the heart tissue. If the coronary vessels become too narrow or completely blocked, a heart attack can result, possibly leading to the death of heart tissue.

Everyone will eventually develop some degree of arteriosclerosis, but what causes it to develop more rapidly in some individuals and progress to the more life-threatening atherosclerosis is not fully understood. What is known is that high blood pressure, along with high levels of cholesterol and triglycerides in the blood, increase the chance of developing atherosclerosis. This means that smoking, poor diet, lack of exercise and obesity are risk factors.

THE LYMPHATIC SYSTEM

The lymphatic system is the second transport system in mammals. The lymphatic system is an open system that consists of lymph vessels, lymph nodes and organs, such as the thymus and spleen. It transports a colourless liquid, called lymph, from the tissues to the heart.

The lymphatic system has several roles. One of its main roles is to return extracellular fluid containing proteins that have leaked out of the capillaries back into the cardiovascular system. Without the constant removal of leaked proteins from the extracellular fluid by the lymph capillaries, fluid would accumulate in the tissues. Once inside the lymphatic system, this fluid is called lymph.

The structure of the lymphatic system is similar to the venous part of the cardiovascular system (Figures 6.2.1 and 6.2.17). Fine lymphatic capillaries join to form increasingly larger vessels, which eventually empty into the large veins near the heart. The structures of lymph capillaries and vessels are similar to the capillaries and veins of the cardiovascular system.

Some of the larger lymph vessels can contract, but most lymph flow results from the external compression of lymph vessels by muscular activity, such as during movement and breathing. When vessels are compressed, the lymph fluid is forced in one direction because of numerous one-way valves, like those in veins, which are located along the lymph vessels. When a person stands still or sits for a long time, the fluid drainage from tissues decreases and causes swelling. This is especially so in the legs, because fluid drainage must work against gravity.

The lymphatic system also plays a vital role in the immune system. Invading pathogens are transported in the lymph to the lymph nodes (Figure 6.2.17), where bacteria, viruses and cancer cells are trapped and destroyed by phagocytes and lymphocytes. This is why your lymph nodes swell up when you have an infection.

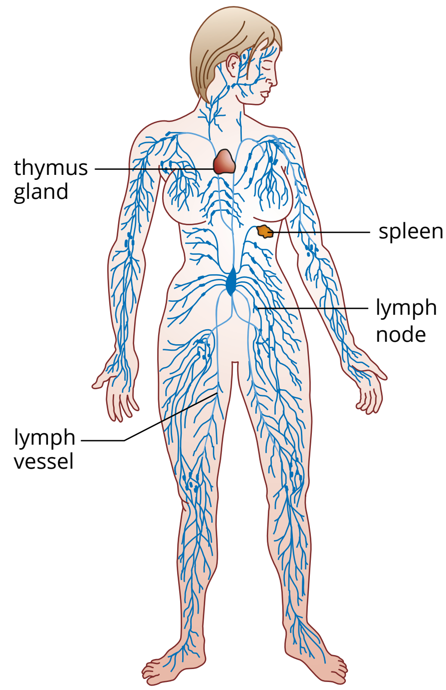


FIGURE 6.2.17 The distribution of lymph vessels throughout the body. The blood circulatory system loses around 3 litres of fluid into the extracellular fluid every 24 hours. The lymphatic system collects and returns this fluid to the cardiovascular system.

Malfunctions of the lymphatic system

One malfunction of the lymphatic system is deep vein thrombosis.

Deep vein thrombosis

People who sit for long periods of time, such as passengers on a long flight, are encouraged to stretch and exercise regularly to assist the movement of lymph and venous blood back to the heart. If they don't, fluid accumulates in the feet, ankles and legs, which can then swell.

This fluid accumulation can lead to a condition called deep vein thrombosis, a blood clot that forms in the veins of the leg. If the clot breaks away and is carried by the bloodstream to a lung, it can lodge there, causing a pulmonary embolism: a blockage of the main artery of the lungs (Figure 6.2.18). A pulmonary embolism can cause difficulty in breathing, chest pain and heart palpitations. If the clot completely blocks an artery, the person can die. Regular exercise, a healthy diet and not smoking all reduce the risk of deep vein thrombosis.

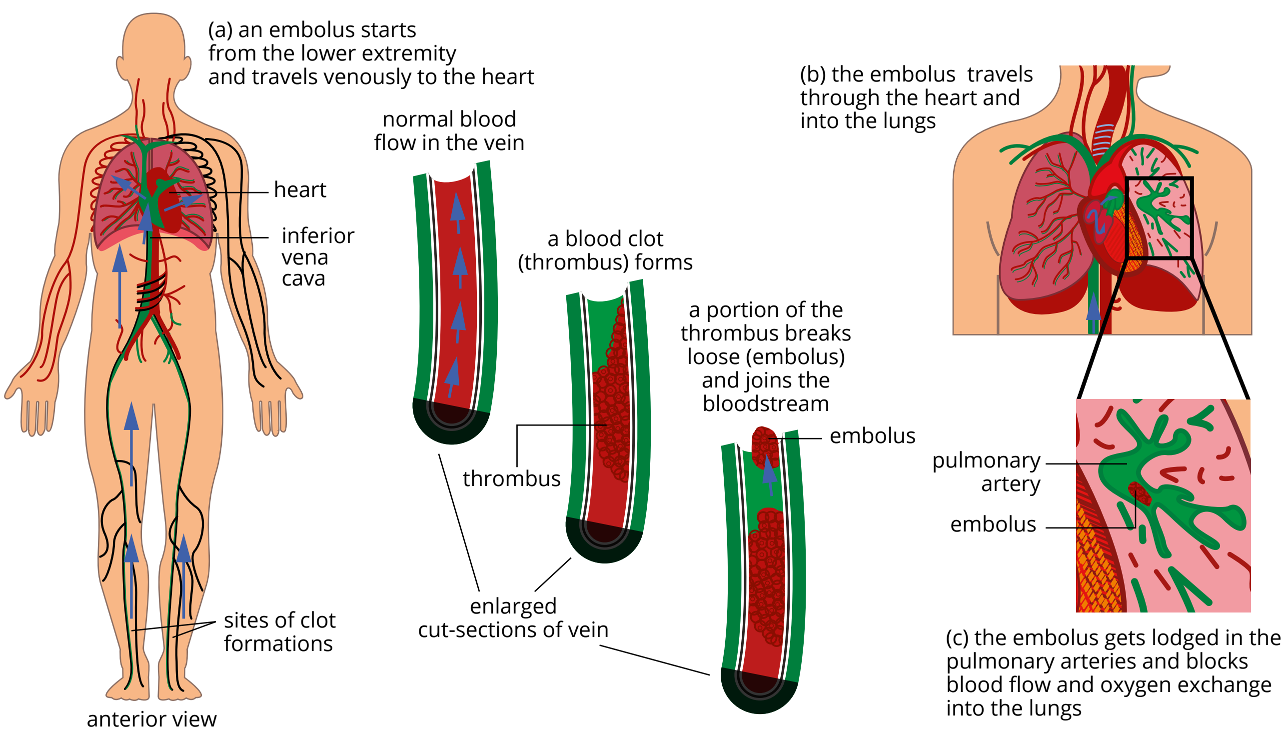


FIGURE 6.2.18 The mechanism of pulmonary embolism resulting from deep vein thrombosis. A pulmonary embolism can occur when a blood clot (embolus) breaks off and lodges in a lung, blocking oxygen exchange.

COMPARING ANIMAL CIRCULATORY SYSTEMS

Many animals have systems that perform similar functions, but the structure can vary greatly between organisms (Figure 6.2.19). The circulatory system is an example of this. In humans and all other vertebrates, the circulatory system is a closed system; the blood flows in a continuous circuit, enclosed within a system of blood vessels and the heart. Some invertebrates, such as earthworms and octopuses, also have a closed system (Figure 6.2.19).

In general, there is a more complete separation of functions in closed circulatory systems than in open circulatory systems.

In open circulatory systems, blood is pumped by the heart but empties into an open, fluid-filled space, the **haemocoel**, which lies between the ectoderm and endoderm of the organism.

Three different circulatory systems that animals use to transport substances throughout the body are examined here: the open circulatory system of insects, the single closed circulatory system of fish, and the double closed circulatory system of amphibians, reptiles, birds and mammals.

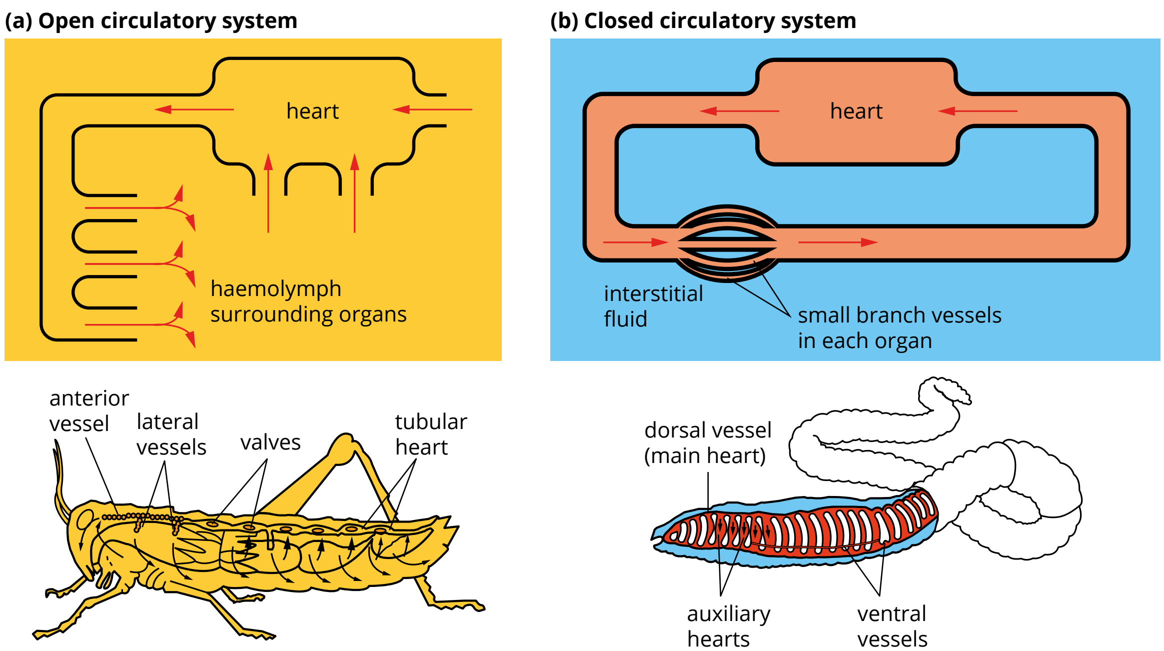


FIGURE 6.2.19 (a) The open circulatory system of a grasshopper and (b) the closed circulatory system of an earthworm have significant differences, but both systems have the same function. They supply the cells of the body with nutrients and oxygen, and transport wastes away from the cells to the organs that excrete them.

Open circulatory systems

Arthropods, including insects, have an open circulatory system. An open circulatory system has a heart or heart-like structure, but no blood vessels (Figure 6.2.19). There is also no distinction between blood and extracellular fluid. This single fluid in open circulatory systems is called **haemolymph**. The haemolymph is in direct contact with all cells, and is kept moving by the beating of the heart and sometimes the movement of the organism itself.

Insect circulatory systems

Insects exchange oxygen and carbon dioxide between the atmosphere and their cells directly. There is no circulatory system involved. These animals, like most invertebrates, are classified as having an open circulation. Gas exchange takes place across a network of fine internal air-filled tubes called **tracheae** and finer

tracheoles. These open to the atmosphere through **spiracles** that can open and close (Figure 6.2.20). The tracheoles branch into smaller and smaller tubes, reaching all tissue. Oxygen moves into the tissues and carbon dioxide enters the tracheae to be expelled from the body.

This process of gas exchange is quite slow, so some larger insects pump their abdomens to accelerate the movement of these gases. Some insects, such as grasshoppers, also have air sacs that can be pumped like bellows to move air through the system.

The structure of this type of respiratory system is one of the factors that limits the size of insects.

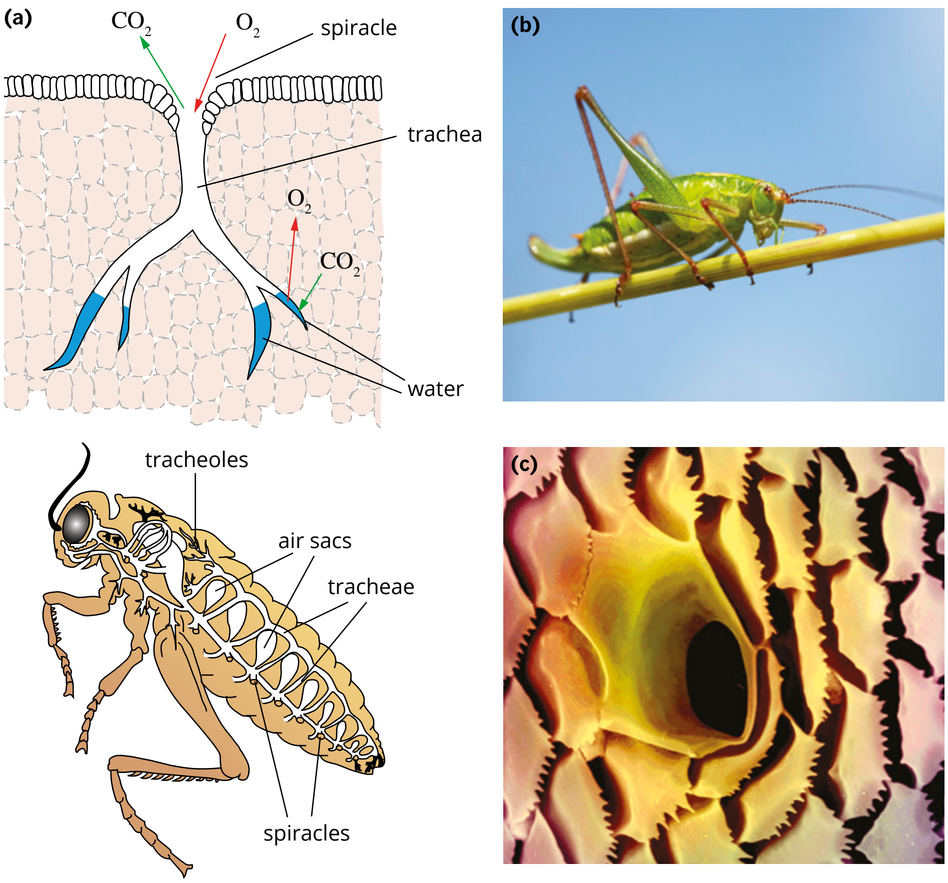


FIGURE 6.2.20 (a) Insects have a system of air-filled tracheae and tracheoles that penetrate every tissue, bringing air into close contact with their cells. (b) Some insects, like this grasshopper, also have air sacs that can be pumped like bellows to move air through the system. (c) Coloured SEM of an ant spiracle

Closed circulatory systems

In closed circulation, a heart is the main propulsive organ, pumping blood and maintaining a high blood pressure in the arteries. Animals with closed circulation can increase oxygen delivery to a tissue very rapidly. This is seen in squids, which can propel and swim very rapidly, maintaining high rates of oxygen uptake. The squid's closed system allows sufficient circulation of oxygen to muscles to support short bursts of activity.

Closed circulatory systems may be single circulatory systems with a two-chambered heart, or double circulatory systems with a four-chambered heart.

Single circulatory systems: fish

FIGURE 6.2.21 The gill arches of this juvenile Mediterranean dusky grouper (*Epinephelus marginatus*) can be seen along the side of its pharynx.

In the circulatory system of a fish, blood travels from the heart to the **gills**, where it absorbs oxygen and releases carbon dioxide. It then flows from the gills to the organs and tissues in the rest of the body, and back to the heart. There is just one circuit from the heart, which is classified as a single circulatory system.

Gills are the principal organs of the respiratory system in fish. Oxygen is not very soluble in water, so the respiratory system needs to be very efficient. Fish gills are composed of several gill arches on either side of the **pharynx** (throat) (Figures 6.2.21 and 6.2.22). Each gill arch is composed of rows of filaments, which in turn are composed of **lamellae**.

The lamellae are closely packed rows of leaf-like structures in which oxygen diffuses into the blood and carbon dioxide diffuses from the blood into the surrounding water. Water is drawn into the pharynx through the mouth and then pushed between the gill arches by compressing the pharynx with the mouth closed. This forces water between individual gill lamellae. The lamellae provide a large surface area for gas exchange and are visibly red because they contain many blood vessels. Water then passes out under the operculum, which covers and protects the fragile gills.

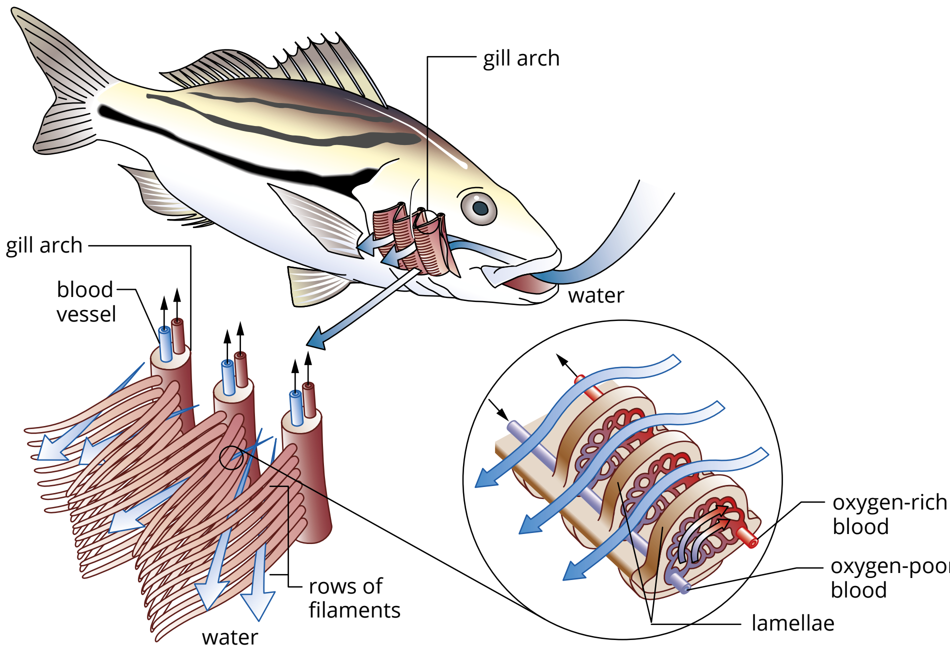


FIGURE 6.2.22 Water flows in one direction across fish gills: through the mouth and pharynx, past the gills and out under the operculum (gill cover).

Double circulatory systems: birds

In the closed circulatory system of birds—as well as amphibians, reptiles and mammals—there are two circuits from the heart. It is therefore classified as a double circulatory system.

In the first circuit, blood passes from the heart to the lungs. It absorbs oxygen and releases carbon dioxide, then returns to the heart. In the second circuit, blood passes from the heart to the organs and tissues in the body, and then back to the heart. This transport system was discussed in detail earlier in this section (see page 276).

Birds have the most efficient respiratory system of all animals. Most birds can fly and are usually very active. This means a bird has a high demand for oxygen and needs to be light.

As with mammals, gas exchange for birds takes place in the lungs. Bird lungs are similar to those of mammals, but instead of alveoli, they have a system of microscopic tubules called air capillaries. In the air capillaries, oxygen moves into the blood and carbon dioxide moves from the blood into the lungs to be exhaled.

Birds have relatively small lungs that do not expand and contract like those of a mammal. Unlike mammals, birds do not have a diaphragm, but instead rely on pressure changes in air sacs to move air in and out of their respiratory system (Figure 6.2.23). The respiratory system of a bird has seven, eight or nine air sacs, depending on the species.

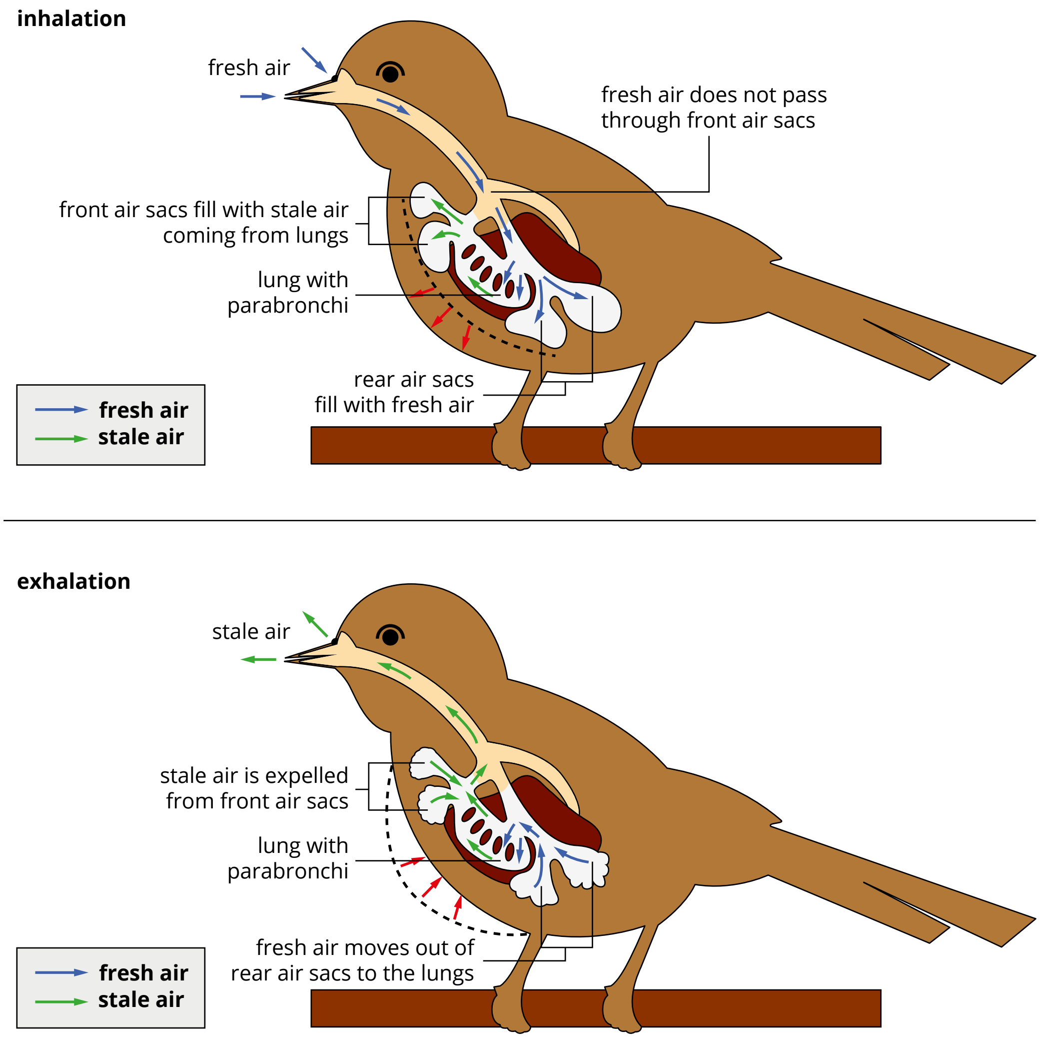


FIGURE 6.2.23 The respiratory system of birds consists of small lungs and several air sacs. This system is extremely efficient and light to meet the demands of flight.

During inhalation, air is drawn into the posterior air sacs and air from the lungs moves into the anterior air sacs. During exhalation, the air sacs collapse, which pushes air from the posterior air sacs into the lungs. At the same time, the air in the anterior air sacs is expelled via the trachea. This process of exhalation creates a one-way flow of fresh air through the bird's lungs, which is extremely efficient. The large number of air sacs also makes the bird very lightweight.

PA 2.5 PA 2.5 PA 2.6 PA 2.6

TRANSPORTING GASES

Oxygen is essential for cellular respiration and the production of energy. The respiratory and cardiovascular systems work together to bring oxygen into the body, transport oxygen to cells throughout the body and remove carbon dioxide (a waste product of cellular respiration) out of the body to the external environment. When oxygen is brought into the lungs, it is carried to cells throughout the body by the oxygen-carrying molecule haemoglobin in the blood. Different molecules in the blood have different affinities for oxygen, which determines how tightly they attach to or release oxygen. Carbon dioxide is carried by the blood to the lungs to be removed from the body via exhalation.

Cellular respiration and the organ system of respiration are very different. Cellular respiration converts nutrients to energy within a cell, while the organ system of respiration in complex animals transports carbon dioxide and oxygen between cells and the external environment.

Carrying oxygen

Maintaining an oxygen concentration gradient across the lung surface requires efficient supply (through ventilation) and removal (by circulation) of the oxygen. But the amount of oxygen that dissolves in water (or blood, which is about 90% water) is very small.

The oxygen-carrying molecule haemoglobin increases the **oxygen-carrying capacity** of the blood. The most important feature of haemoglobin is that it can combine reversibly with oxygen.

Increasing the oxygen-carrying capacity of blood reduces the amount of energy that must be spent pumping blood. Because each millilitre of blood carries much more oxygen, an animal can have a much smaller volume of blood, and pump it around the body more slowly, while still supplying the same amount of oxygen to its cells.

Haemoglobin

Oxygen is relatively insoluble in blood: only 0.2 mL of oxygen gas dissolves in 100 mL of blood. The carrying capacity of mammalian blood is increased 100 times by the presence of the red respiratory protein haemoglobin, which is carried in red blood cells. Mature red blood cells are little more than cell membranes filled with haemoglobin.

Haemoglobin is a complex protein containing iron. Four oxygen molecules can combine with each haemoglobin molecule (Figure 6.2.24). In areas of high oxygen concentration, such as in the blood in vessels in the lungs, haemoglobin combines with oxygen to form oxyhaemoglobin. In areas of low oxygen concentration, such as in muscles that are exercising, oxygen is released (dissociated) from the oxyhaemoglobin. The percentage of oxygen concentration in exercising muscles, tissues and lungs therefore varies. This relationship can be seen in Figure 6.2.24.

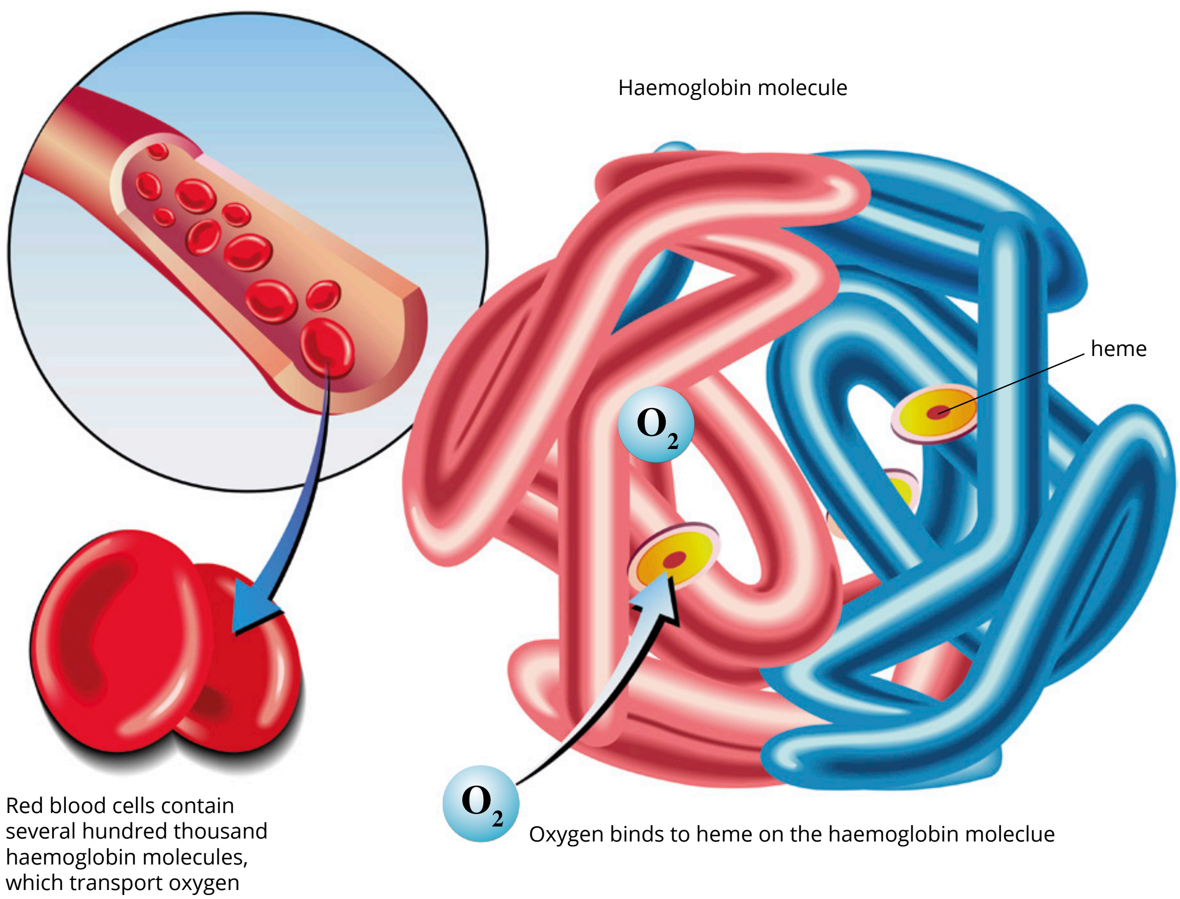


FIGURE 6.2.24 3D structure of a haemoglobin molecule. Haemoglobin is responsible for binding oxygen molecules in red blood cells.

Oxygen in the tissues

The oxygen-haemoglobin dissociation curve represents how blood carries and releases oxygen throughout the body (Figure 6.2.25). The percentage of haemoglobin (Hb) saturated with oxygen (O_2) indicates how readily haemoglobin binds to oxygen molecules. Haemoglobin's affinity for oxygen is affected by many factors. An increased oxygen affinity shifts the curve to the left and a decreased oxygen affinity shifts the curve to the right.

In resting humans, haemoglobin is almost 100% saturated with oxygen in the lungs, and about 75% saturated in other tissues (Figure 6.2.25). This means that only about one-quarter of the oxygen carried by the blood throughout the body is taken up from capillaries and used by cells for cellular respiration. The remaining oxygen in the blood is a reserve, available for use when oxygen demand increases—for example, during exercise, when blood oxygen saturation may drop to 25%. An adequate oxygen supply is so critical to our survival that we need a considerable reserve for use during emergencies.

Our muscles are red because they also contain a form of haemoglobin called **myoglobin**. Myoglobin carries a reserve store of oxygen that muscles can use for a limited period if the amount of oxygen in the blood suddenly decreases to a very low level. This situation could arise if a blood vessel were temporarily blocked, or during strenuous exercise. When blood supply is restored, the myoglobin oxygen store is immediately refilled from the blood. Myoglobin has a higher affinity for oxygen than haemoglobin and therefore can take oxygen from it. This also means that haemoglobin releases large amounts of its bound oxygen to exercising muscle before the myoglobin releases its store, making it a true emergency resource.

The haemoglobin of a fetus binds oxygen with a greater affinity than adult haemoglobin, therefore extracting haemoglobin from the mother's blood in the placenta. This means that at lower partial pressures of oxygen, the fetal haemoglobin loads oxygen more easily than adult haemoglobin. This would cause a shift to the left in the oxygen–haemoglobin dissociation curve (Figure 6.2.25). Myoglobin has a stronger affinity for oxygen than does haemoglobin.

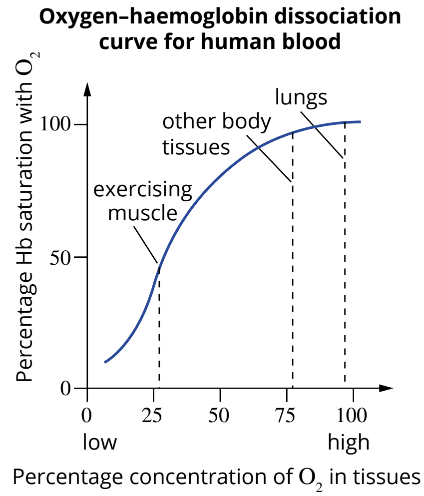


FIGURE 6.2.25 An oxygen–haemoglobin dissociation curve for human blood shows the concentration of oxygen in different tissues in the body. (Hb: haemoglobin)

Anaemia

Anaemia is a condition in which there are insufficient red blood cells, or the quality of the red blood cells or the haemoglobin is low. The most common cause of anaemia is a deficiency of iron in the diet. Other causes include failure to absorb iron because of disease, heavy menstruation, or inherited disorders such as sickle cell disease.

Anaemia results in pale skin, tiredness, muscle weakness, headaches and problems with concentration. Treatment is determined by the underlying cause, but can involve a change in diet or taking iron supplements. In extreme cases, treatment can even involve oxygen therapy and blood transfusions.

Carrying carbon dioxide

Carbon dioxide, which is produced by cellular respiration, must be carried in body fluids to an external surface where it can be released to the environment. When it combines with water, carbon dioxide forms a weak acid called carbonic acid, which dissociates into bicarbonate and hydrogen ions. This causes a decrease in pH. As a result, carbon dioxide can be carried in solution only in limited amounts.

In mammals, about 7% of the carbon dioxide carried by blood is dissolved in the blood plasma. About 23% combines with haemoglobin molecules (forming carbamino-haemoglobin), but at a different site on the haemoglobin molecule from where oxygen binds. Carbamino-haemoglobin is still able to combine with oxygen. The remainder of the carbon dioxide produced in working tissues passes into red blood cells, where it is converted to hydrogen carbonate ions, and then passes out to be transported in the plasma.

When blood reaches the lungs, the hydrogen carbonate moves back into the red blood cells, where it is converted to carbon dioxide for release during breathing.

The Bohr effect

In 1904, Danish scientist Christian Bohr discovered that the affinity of haemoglobin for oxygen is inversely related to the acidity of blood and the concentration (or partial pressure) of carbon dioxide.

Bohr found that haemoglobin binds more tightly to oxygen in blood with a low carbon dioxide concentration (low acidity/high pH). This is because haemoglobin loses hydrogen ions as pH increases, changing its structure and increasing its oxygen-binding capacity. As haemoglobin's affinity for oxygen increases, the oxygen–haemoglobin dissociation curve shifts to the left.

The opposite occurs as carbon dioxide concentration increases (high acidity/low pH); haemoglobin picks up hydrogen ions and its affinity for oxygen decreases. As haemoglobin's affinity for oxygen decreases, the oxygen–haemoglobin dissociation curve shifts to the right. This is the **Bohr effect** (also known as the Bohr shift) (Figure 6.2.26).

The Bohr effect explains how haemoglobin picks up and releases oxygen where needed in the body. As blood nears the lungs, the concentration of carbon dioxide decreases (decreasing acidity) and the affinity of haemoglobin for oxygen increases. This allows haemoglobin to bind to the oxygen entering the blood from the lungs and transport it to cells throughout the body. The opposite occurs in tissues where oxygen needs to be released (dissociated) from haemoglobin. As blood moves away from the lungs, the concentration of carbon dioxide increases (increasing acidity) and the affinity of haemoglobin for oxygen decreases. This allows oxygen to be released from the haemoglobin in red blood cells to cells throughout the body where it is needed for cellular respiration.

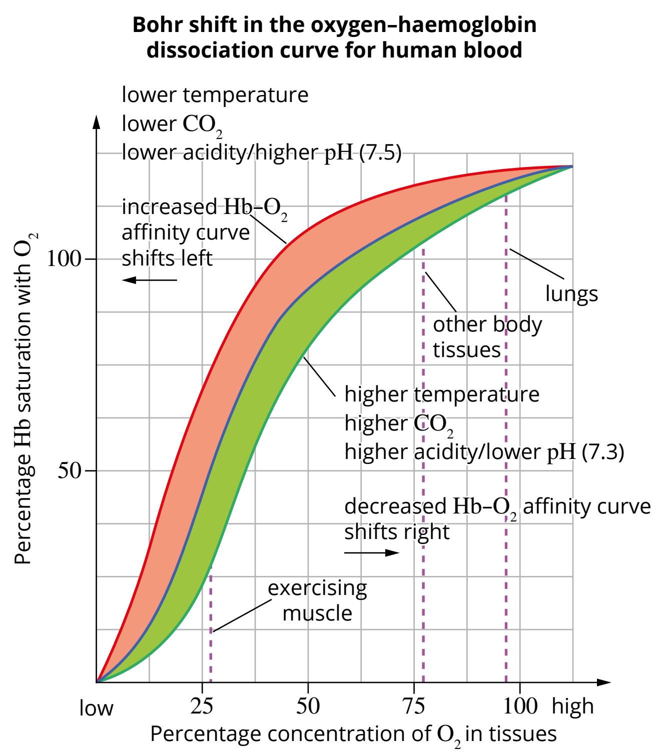


FIGURE 6.2.26 The Bohr shift is the shift of the oxygen–haemoglobin dissociation curve with a change in pH. The oxygen binding affinity (represented by percentage haemoglobin [Hb] saturation with O_2) is related to the acidity (concentration of hydrogen ions) and carbon dioxide concentration of the blood. A decrease in carbon dioxide (increase in pH) increases haemoglobin's affinity for oxygen and shifts the curve to the left (red line). An increase in carbon dioxide (decrease in pH) decreases haemoglobin's affinity for oxygen and shifts the curve to the right (green line). (Hb: haemoglobin)

6.2 Review

SUMMARY

- Mammals have two transport systems: the cardiovascular system (or circulatory system) and the lymphatic system.
- The cardiovascular system:
  - consists of the heart, veins, arteries, capillaries and blood
  - transports nutrients and oxygen to all cells in the body and transports metabolic wastes away from all cells in the body
  - has two sequential circulation pathways: pulmonary circulation (transports blood to and from the lungs) and systemic circulation (transports blood to and from the rest of the body).
- Mammalian blood is a fluid containing cells and cellular fragments. Blood is composed of plasma, red blood cells (erythrocytes), white blood cells (leukocytes) and platelets (thrombocytes).
- The blood vessels of the cardiovascular system include arteries, veins and capillaries. Each vessel's structure is directly related to its function.
- Blood pressure is caused by the contraction of the ventricles. Blood pressure can be measured using a sphygmomanometer.
- The lymphatic system:
  - consists of lymph vessels, lymph nodes and organs, such as the thymus and spleen
  - transports a colourless liquid called lymph
  - transports lymph in one direction, from the tissues to the heart
  - has several functions, one of which is returning extracellular fluid containing proteins that have leaked out of the capillaries back into the cardiovascular system.
- Animals can have open or closed transport systems.
  - An open circulatory system has a heart or heart-like structure, but no blood vessels. Arthropods, including insects, have open circulatory systems.
  - Closed circulatory systems may be single circulatory systems with a two-chambered heart, or double circulatory systems with a four-chambered heart. Fish have single circulatory systems. Amphibians, reptiles, birds and mammals have double circulatory systems.
- The respiratory and cardiovascular systems work together to transport oxygen into the body and transport carbon dioxide out of the body.
- Maintaining an oxygen concentration gradient across the lung surface requires efficient supply (through ventilation) and removal (by circulation) of the oxygen.
- The oxygen-carrying molecule haemoglobin increases the oxygen-carrying capacity of the blood.
- Haemoglobin is a complex protein containing iron. Four oxygen molecules can combine with each haemoglobin molecule.
- Our muscles are red because they also contain a form of haemoglobin called myoglobin. Myoglobin carries a reserve store of oxygen that muscles can use if the amount of oxygen in the blood decreases to a low level.
- Carbon dioxide in the blood causes a change in pH and alters the binding of oxygen to haemoglobin. This is known as the Bohr effect.
- The haemoglobin–oxygen dissociation curve represents how blood carries and releases oxygen throughout the body. If haemoglobin's affinity for oxygen increases, the curve shifts to the left. If haemoglobin's affinity for oxygen decreases, the curve shifts to the right.

6.2 Review *continued*

KEY QUESTIONS

1 What system in multicellular organisms provides cells with nutrients and removes wastes from the cell?

2 Describe the two pathways through which blood is circulated in mammals.

3 Match each of the following heart structures with its function.

Structure	Function
aorta	deoxygenated blood is pumped by the right ventricle and flows to the lungs
left atrium	deoxygenated blood returns from the body to the right atrium
left ventricle	oxygenated blood is pumped from the left ventricle and flows to the rest of the body
pulmonary artery	oxygenated blood returns from the lungs to the left atrium
pulmonary veins	receives deoxygenated blood from the right atrium and pumps it to the lungs
right atrium	receives deoxygenated blood returned from the body
right ventricle	receives oxygenated blood from the left atrium and pumps it to the rest of the body
venae cavae	receives oxygenated blood from the lungs

4 What are the fluid and cellular components of blood?

5 **a** Which two forces result in filtration of fluids into and out of capillaries, and in which direction do each of these exert pressure?

b What impact do these forces have on fluid filtration in capillaries?

6 Outline the functions of the lymphatic system.

7 Blood is a liquid tissue containing glucose, urea, plasma proteins and other components. List the other components of blood.

8 Complete the following summary table on open and closed circulatory systems in animals.

	Open circulatory system	Closed circulatory system
Organism example		
How blood is pumped		
Contact of blood with body tissues		
Pressure of blood flow		
Speed of blood flow		
Regulation of blood flow through tissues and organs		

9 How is fetal haemoglobin different to adult haemoglobin?

Chapter review

KEY TERMS

active transport
adhesion
anaemia
aorta
arteriole
artery
atrium
blood
blood plasma
blood vessel
Bohr effect
capillary
cardiovascular system
Casparian strip
chlorenchyma
closed circulatory system
cohesion
companion cell
connective tissue
coronary circulation
deoxygenated blood
diastolic pressure
diffusion
gill
guttation
haemocoel
haemoglobin
haemolymph
heart
hydrostatic pressure
lamellae
lignin
lumen
lymph
lymphatic system
lymphocyte
myoglobin
open circulatory system
organic solute
osmosis
osmotic pressure
oxygenated blood
oxygen-carrying capacity
parenchyma
phagocyte
pharynx
phloem
plasmodesmata
platelet
pulmonary artery
pulmonary circulation
pulmonary vein
red blood cell
root pressure
sclerenchyma
sieve tube
sink
source
spiracle
starch
systemic circulation
systolic pressure
tracheae
tracheid
translocation
transpiration
transpiration stream
transpiration–cohesion–tension theory
tunica
valve
vascular bundle
vein
ventricle
venule
white blood cell
xylem
xylem vessels

REVIEW QUESTIONS

1 Create a summary table comparing xylem and phloem transport. Outline what each tissue transports and the direction of transport.

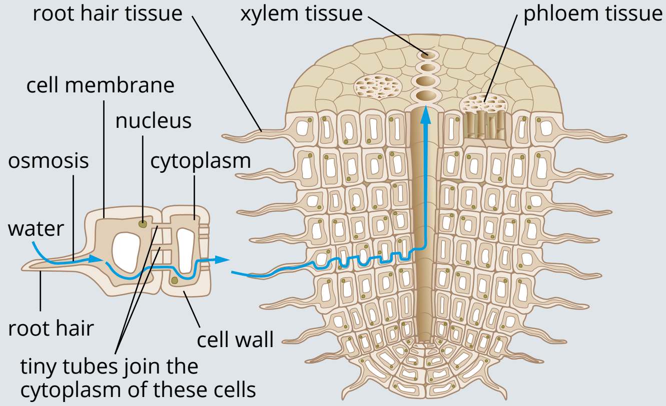
2 What is the function of the pit structures in xylem tissue?

3 Compare the similarities and difference between xylem vessels and xylem tracheids.

4 **a** Explain how a tree is killed by ringbarking.
b How does unintentional ringbarking occur, and how can it be treated?

5 In autumn, the leaves of deciduous trees change colour and eventually fall. The change in colour is due to the movement of nutrients out of the leaves for storage. This involves:
A xylem and phloem
B only the xylem
C only the phloem
D diffusion

6 Describe the pathway of water absorption in the diagram of plant root tissue below.



7 **a** What is the association of gas exchange with transpiration in plants?
b How does wind affect transpiration rates?
c Why is the rate of transpiration lower at night?

8 Explain the role of red blood cells and white blood cells in the body.

9 Why is atherosclerosis especially dangerous when found in the coronary arteries?

10 Discuss some of the adaptations that plants living in harsh environments, such as deserts, have developed to achieve water transport.

11 What is the name of the protein that binds to oxygen in red blood cells? What condition can result if this protein is deficient?

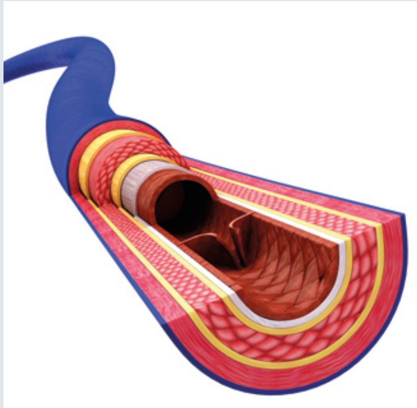
12 Describe the features and functions of the cardiovascular system and the lymphatic system.

13 Which side of the heart has thicker muscular tissue, and why? How does this affect the blood pressure in the different areas of the heart?

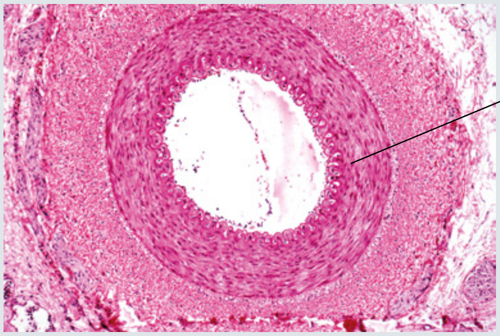
14 Complete the summary table below comparing arteries, veins and capillaries.

	Arteries	Veins	Capillaries
Function	send blood away from heart		
Pressure		low	
Wall thickness		thin	
Wall layers			consist of a single layer of flattened epithelial cells
Muscle and elastic fibres	large amounts		
Valves	no		

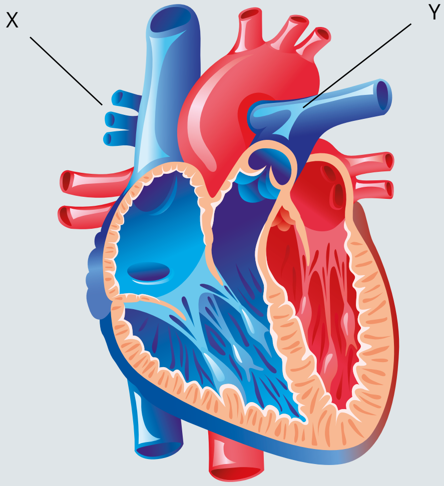
15 The image below shows a blood vessel. State the type of vessel and reasons to support your choice.



16 The image below is a light micrograph of a cross-section of a blood vessel. State the blood vessel type and name the layer labelled X.



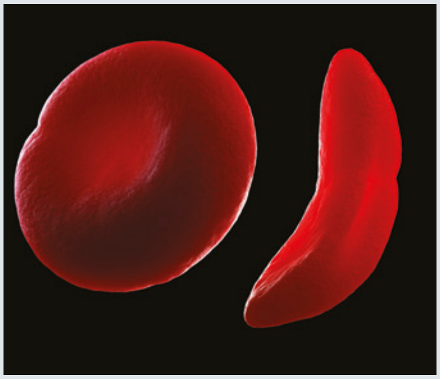
17 In the diagram of the heart below, state what structure X and Y are and what each structure carries.



18 When blood is returning to the mammalian heart in a pulmonary vein, where does this blood first drain into?

19 Outline the passage of blood in the human cardiovascular system as it leaves the lungs. Which vessels does it travel in and where does it travel to?

20 Sickle cell disease is a red blood cell disorder. People with sickle cell disease have abnormal haemoglobin in their red blood cells. As a consequence, the red blood cells become sickle-shaped and inflexible.



Based on your understanding of the functions of red blood cells, what are the effects of having sickle-shaped red blood cells on the functioning of the cardiovascular system?

21 A common problem for passengers on a long plane trip is that upon arrival, their feet have become so swollen that they will not fit into their shoes. Airlines recommend exercises to help reduce this problem.

a Explain what causes feet to swell during air travel.

b How could exercise help?

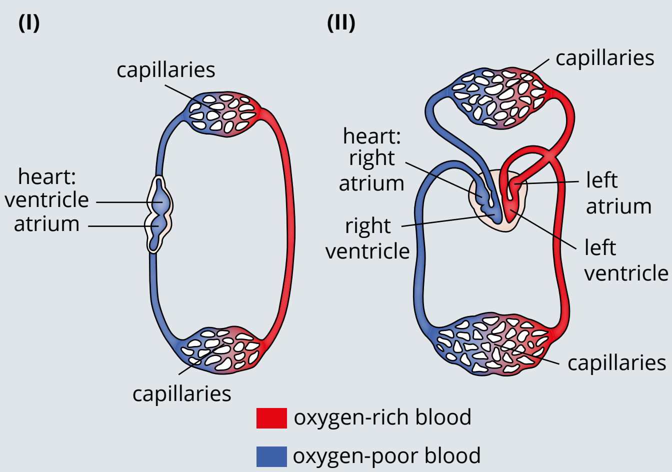
c Deep vein thrombosis is a major concern for long-distance travellers. Explain why clots are likely to form and how this can be prevented.

22 What is the difference between an open and closed circulatory system?

23 Compare the circulatory and respiratory systems of humans, fish, birds and insects by completing the table below.

	Human	Fish	Bird	Insect
Open or closed circulatory system				
Double or single circulatory system				
Pressure of blood flow				
Site of gas exchange				
Efficiency of gas exchange				

24 The following circulatory systems are from two different organisms: a fish and a panda.



a Are these systems classified as open or closed circulatory systems?

b Identify which system is a single circulatory system and which is a double circulatory system.

c State which system belongs to each animal. Provide reasons to support your answer.

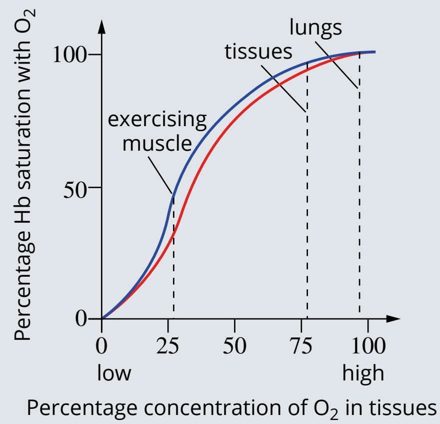
d Label the pulmonary circuit and systemic circuit on the diagram and state which system these circuits are found in.

e Describe how the environment of these two organisms influences the type of circulatory system they have.

25 How does the carbon dioxide concentration of the blood affect the release of oxygen in tissues?

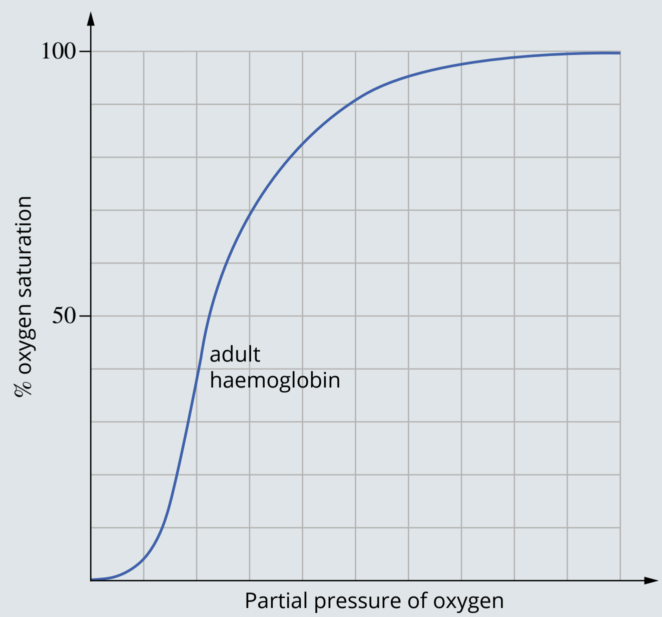
26 Using the information in the following graph, discuss the relationship between oxygen, haemoglobin (Hb) and the cardiovascular system.

Oxygen–haemoglobin dissociation curve for human blood



27 What causes the oxygen–haemoglobin dissociation curve to shift to the right (red line on graph)?

28 The following oxygen–haemoglobin dissociation curve shows the oxygen affinity (% oxygen saturation) of adult haemoglobin.



a What is haemoglobin composed of?

b Describe the affinity that fetal haemoglobin and myoglobin have with oxygen.

c Using your response from Question b), redraw the graph, including a dissociation curve for fetal haemoglobin and myoglobin.

29 After completing the Biology Inquiry on page 266, reflect on the inquiry question: How does the composition of the transport medium change as it moves around an organism? Describe how the transport mediums in plants and animals support their biological functions.

MODULE 2 • REVIEW

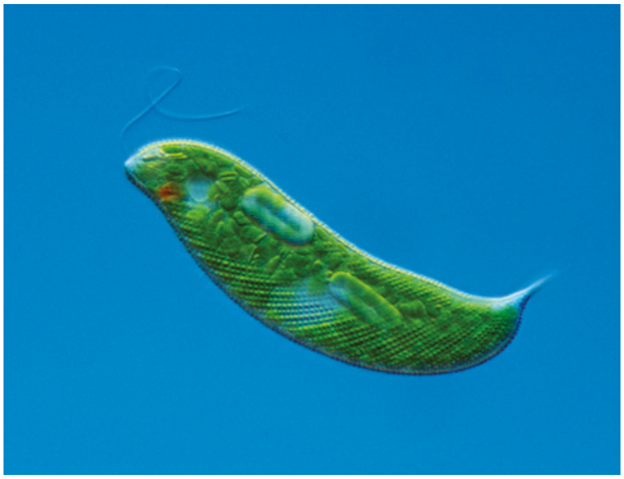
REVIEW QUESTIONS

WS 2.9 WS 2.10 MR 2

Organisation of living things

Multiple choice

1 The organism below is known as *Euglena* and it is described as being a eukaryotic protist. Select the correct explanation for this description.



A *Euglena* is a unicellular organism without a central nucleus.
B *Euglena* is a unicellular organism with a membrane-bound nucleus.
C *Euglena* lives in a colony of similar organisms to increase its chance of survival.
D *Euglena* photosynthesises its own food and is classified as a type of plant.

2 Which statement best describes the advantages of being a multicellular organism?
A more energy is required for survival and organisms have longer generation times
B cells have specialised functions and are dependent on each other
C more energy-efficient and organisms can be larger in size
D organisms are slower to adapt to environmental changes

3 Which one of the following lists contains only the names of organs?
A root, leaf, stem, fruit
B artery, eye, skin, liver
C stoma, flower, fruit, chloroplast
D kidney, nucleus, ovary, lung

4 Which one of the following lists contains only the names of tissues?
A xylem, phloem, cuticle, vacuole
B muscle, nerve, connective, blood
C cardiac, digestive, epithelial, spleen
D chloroplast, mitochondrion, nucleus, cytoplasm

5 Which one of the following lists contains only the names of systems?
A excretory, immune, respiratory, epidermal
B circulatory, muscular, nervous, nuclear
C root, phloem, xylem, fruit
D endocrine, skeletal, reproductive, digestive

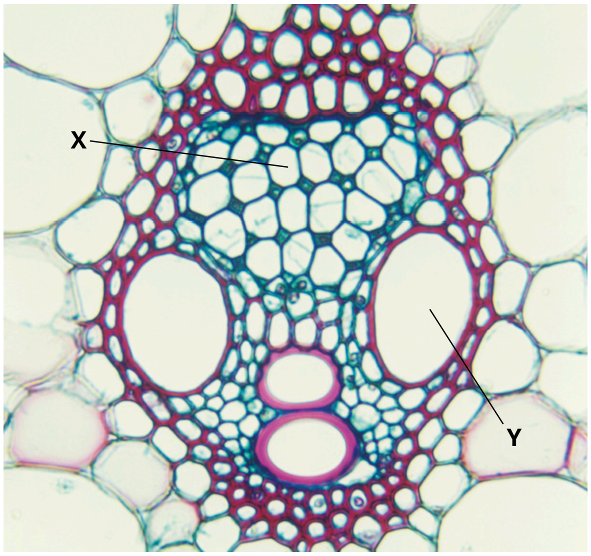
6 Identify the distinction between cell specialisation and cell differentiation.
A Cell differentiation is the process of change from an undifferentiated cell to a specialised cell that performs a specific function.
B Cell specialisation is the process of change from a differentiated stem cell into a fully functional cell.
C Cell specialisation is when one differentiated cell carries out all the functions to sustain life.
D Cell differentiation is when one specialised cell carries out all the functions to sustain life.

7 Which list has the levels of organisation in the correct order from largest to smallest?
A organelle, specialised cell, system, organ, tissue, organism
B organism, system, tissue, organ, specialised cell, organelle
C organism, system, organ, tissue, organelle, specialised cell
D organism, system, organ, tissue, specialised cell, organelle

8 Which of the following groups (A, B, C or D) contains the correct energy sources of photoautotrophs, chemoautotrophs and heterotrophs?

	Photoautotrophs	Chemoautotrophs	Heterotrophs
A	light	light	inorganic compounds
B	light	inorganic compounds	organic compounds
C	inorganic compounds	light	organic compounds
D	inorganic compounds	inorganic compounds	inorganic compounds

9 Identify the microscopic structures X and Y in this transverse section of a plant stem.



A X is tracheids and Y is a companion cell
B X is a vascular bundle and Y is pith
C X is phloem and Y is xylem
D X is xylem and Y is phloem

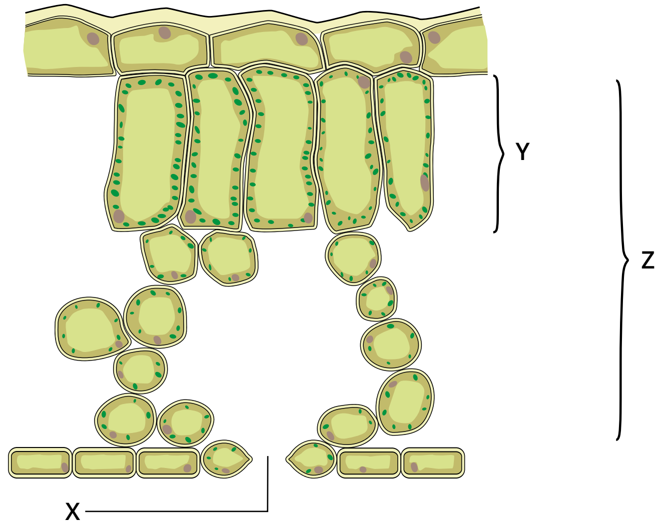
10 Which of the following would be visible to the naked eye in a plant dissection?
A root hairs
B chloroplasts
C vacuole
D mesophyll

11 Which of the following is the most accurate description for the structure and function of plant root hairs?
A extensions from the main root to help anchor the plant into the soil
B extensions of epidermal cells that increase diffusion of water
C extensions of xylem that increase surface area for uptake of water
D extensions of epidermal cells that increase surface area for uptake of water

12 Identify the group (A, B, C or D) that contains the correct labels for structures X, Y and Z in the diagram showing the cell structure of a leaf.

	X	Y	Z
A	guard cell	upper epidermis	palisade layer
B	air space	mesophyll	cytoplasm
C	stoma	epidermis	spongy layer
D	stoma	palisade layer	mesophyll

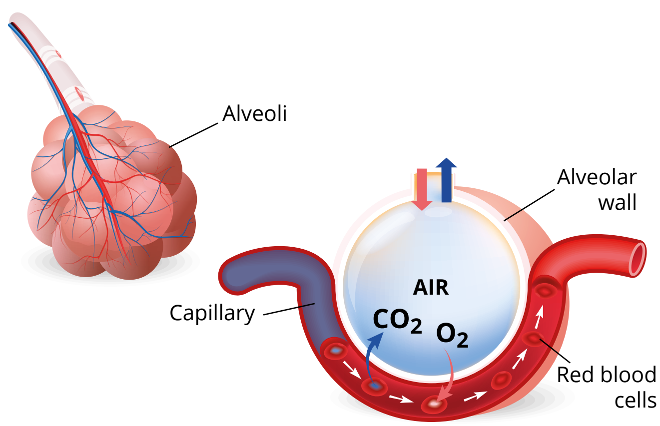
Cell structure of a leaf



13 How is most of the carbon dioxide transported away from the cells in humans?
A as hydrogen carbonate ions in the plasma
B attached to haemoglobin on red blood cells
C dissolved in liquid form in the blood plasma
D in tiny gas bubbles in the blood

14 What are the features for optimal gas exchange?
A dry and well-ventilated cell membranes
B a large surface area and efficient transport system
C an impermeable, large surface area with a blood supply
D a good supply of oxygenated blood to a well-ventilated surface

15 For the diagram below of alveoli in the human lung, identify correct labels for the red and blue arrows.



A red arrow = red blood cells; blue arrow = plasma
B red arrow = carbon dioxide; blue arrow = water vapour
C red arrow = carbon dioxide; blue arrow = oxygen
D red arrow = oxygen; blue arrow = carbon dioxide

16 The image below shows the tail end of a dragonfly larva that lives in freshwater until it changes into adult form. What is the most likely function for the three appendages?

A locomotion
B gas exchange
C attracting a mate
D absorbing nutrients

17 Which of the following choices (A, B, C or D) correctly lists the nutrient and gas requirements of heterotrophs and photoautotrophs?

	Photoautotrophs	Heterotrophs
A	light, water	water, carbon dioxide
B	carbon dioxide, water	organic compounds, oxygen
C	organic compounds, water	organic compounds, light
D	organic compounds, oxygen	minerals, carbon dioxide

18 Choose the most accurate description for the process of physical digestion in mammals.
A crushing food into shapes that can be swallowed easily
B using enzymes to break up food
C using stomach acid to dissolve food
D breaking large pieces of food into smaller pieces

19 Which group (A, B, C or D) correctly identifies the type of digestion used by the animals listed?

	Extracellular digestion	Intracellular digestion
A	mammals, birds, sea stars	mussels, protozoa, *Amoeba*
B	fungi, carnivorous plants, flatworms	reptiles, earthworms, ants
C	spiders, sponges, insects	tapeworms, fungi, carnivorous plants
D	fish, *Amoeba*, sea stars	corals, flatworms, insects

20 Which of the following groups (A, B, C or D) lists the correct sequence of sites for the process of digestion in humans?
A mouth, oesophagus, liver, small intestine, large intestine, anus
B mouth, stomach, pancreas, large intestine, small intestine, anus
C mouth, oesophagus, stomach, small intestine, large intestine, anus
D mouth, oesophagus, stomach, gall bladder, small intestine, anus

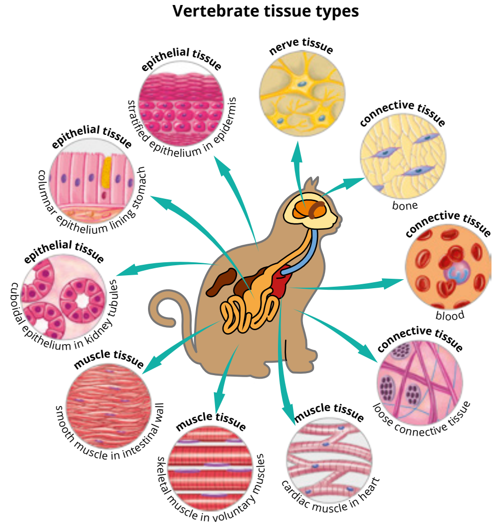
Short answer

21 Identify the level of organisation and function of each of these animal structures.

Structure	Level of organisation	Function
heart	organ	pumps blood around the body
leucocyte		
blood		
skin		
muscle		
endocrine		
neuron		
lymphatic		

22 The diagram below shows the organisation of tissues in a multicellular organism. Biologists describe a hierarchical organisation of cells, tissues, organs and systems for a complex animal like this.

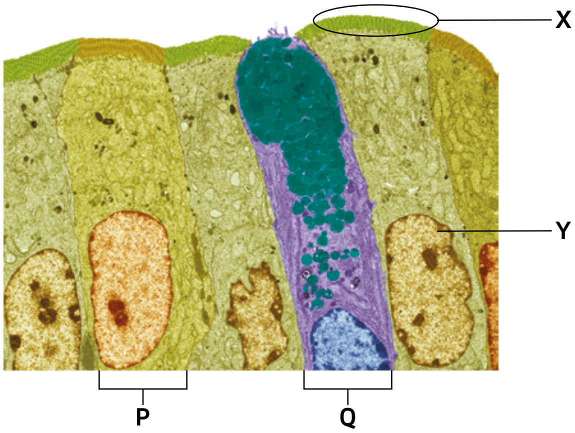
Vertebrate tissue types



a Construct a flow chart diagram to depict the structural hierarchy of a system in a multicellular organism, adding a description of the structural level and an example of a structure at each level.
b Explain why it is useful to use a hierarchy like this.

23 Draw the internal structure of a leaf in a three-dimensional diagram and label the structures.

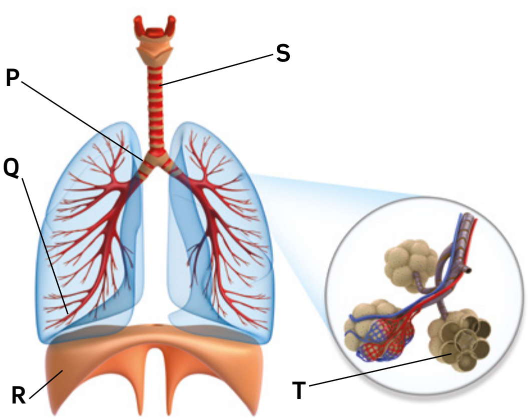
24 The following electron micrograph shows some of the cells in the mammalian digestive system.



a Name structures X and Y.
b Identify the type of cell labelled P.
c In which part of the digestive system was this image taken? Explain your answer.

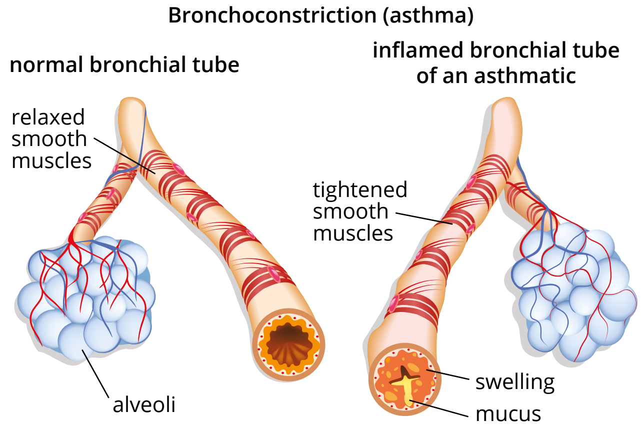
25 Pepsin is an enzyme that is released into the stomach of humans (pH 1.5–3.5, 37°C), where it breaks down proteins into polypeptides.
a Is this an example of physical or chemical digestion?
b Clarify the difference between a protein and a polypeptide. In your answer, make it clear why proteins have to be digested before they can be absorbed into the bloodstream.
c Explain how you would expect the activity of pepsin to change as:
i the temperature increased from 37°C to 45°C
ii the pH increased above 5.

26 The following diagram shows the structure of the human respiratory system.



a Identify structures P, Q, R, S and T.
b Describe how the movement of the rib cage and diaphragm results in air moving into T.

27 The diagram below shows a normal bronchus and a bronchus during an asthma attack.



a What symptoms will a person have during an asthma attack?
b Explain the reason for the symptoms listed in Question a.
c Asthma interferes with one important component of the gas exchange process. How does this happen?

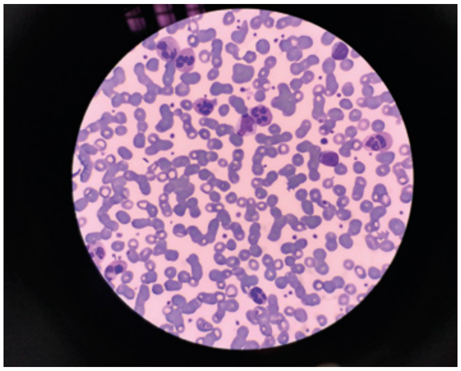
28 Describe the transpiration–cohesion–tension theory for movement of water in the transport system of a plant. Use a diagram to support your answer.

29 The following table compares the relative thickness of three major blood vessels.

Blood vessel	Mean diameter (mm)	Mean wall thickness (mm)
X	4.0	1.0
Y	0.008	0.0005
Z	5.0	0.5

a Identify the types of blood vessels represented by X, Y and Z.
b Explain the differences in diameter and wall thickness between the three blood vessels.

30 a Identify what is shown in the image below.

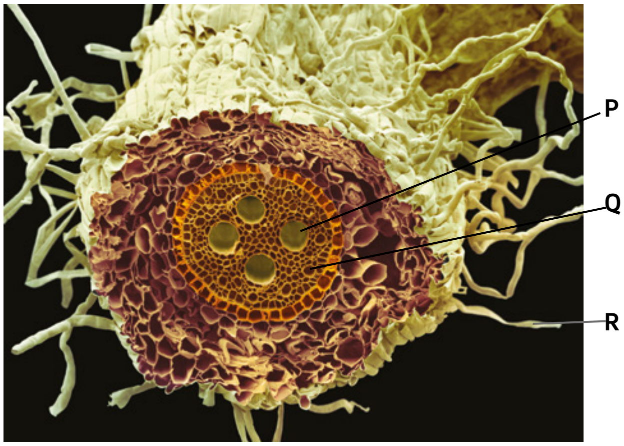


b Compare the two specialised components that can be seen in this image and state a function of each.
c Explain why the image is this colour.

MODULE 2 • REVIEW

Extended response

31 The following image shows a scanning electron micrograph of a root.



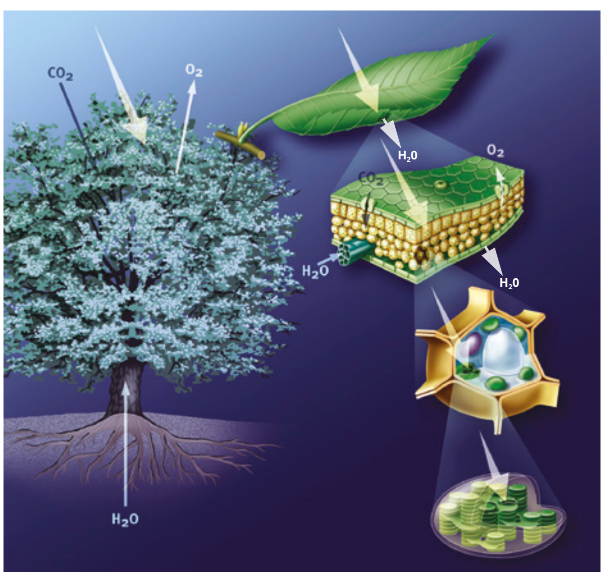
a Identify structures P and Q.

b Explain how cell R is specialised in its function.

c The root is an organ. Using the root as an example, outline how the cells are organised to form an organ.

d Outline how structure P is involved in the transport and eventual loss of water.

32 The image below shows plant structures that are associated with the process of photosynthesis. Use information from the image to assist with answering the questions.



a Write the word and chemical equations for photosynthesis.

b Why are leaves so numerous on plants?

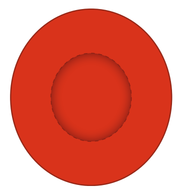
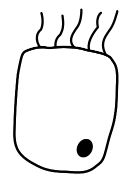
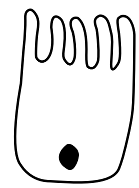
c Explain the functional significance of leaf shape.

d Name the specialised organelle shown in the image and use a table to describe how its structure supports its function.

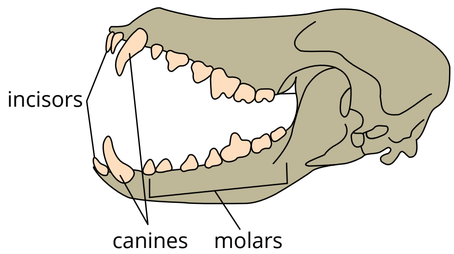
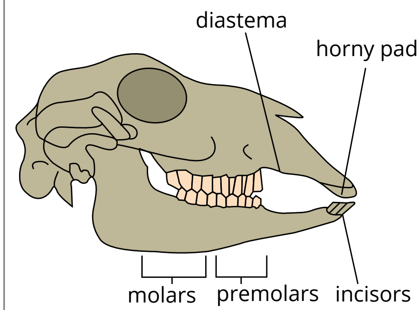
e Outline how the products of photosynthesis produced in the leaves are moved to other parts of the plant. Use a diagram to support your answer.

f Evaluate the theory of endosymbiosis to explain the origin of chloroplasts.

33 The following table shows three specialised cells from three human organ systems. Information about disorders of these systems is given. Using your knowledge of organ systems, complete the table with information about the function of the cell and how the cell is involved in each disorder.

	Red blood cell	Ciliated epithelial cell lining trachea and bronchi	Epithelial cell lining small intestine
			
Organ system			
Specialised cell structure		presence of cilia on surface facing the airway	
Specialised cell function		rhythmic waving or beating motion to sweep mucus, particles and microbes out of airways	
Disorder of the system	haemolytic anaemia: abnormal breakdown of red blood cells	chronic obstructive pulmonary disease: can be caused by cigarette smoke, which damages ciliated epithelial cells	coeliac disease: damage to villi (finger-like projections) in the small intestine
How cell is involved in the disorder			

34 The following table compares the length of the digestive tract with the body length of two organisms, organism A and organism B. The skulls of the two organisms are also shown.

	Organism A	Organism B
Skull		
Ratio of body length to entire digestive tract	1 : 7	1 : 27
Ratio of body length to small intestine	1 : 6	1 : 25

a One role of teeth in mammals is to break food into smaller pieces. Explain the benefit of this.

b Propose which diet organism B would have and justify your choice.

c Explain the difference in the length of the digestive tracts of the two animals.

d Assuming both organisms are mammals, suggest an example of each.

e Summarise the digestive products of each organism and how you would expect them to be absorbed from their small intestines into the bloodstream.

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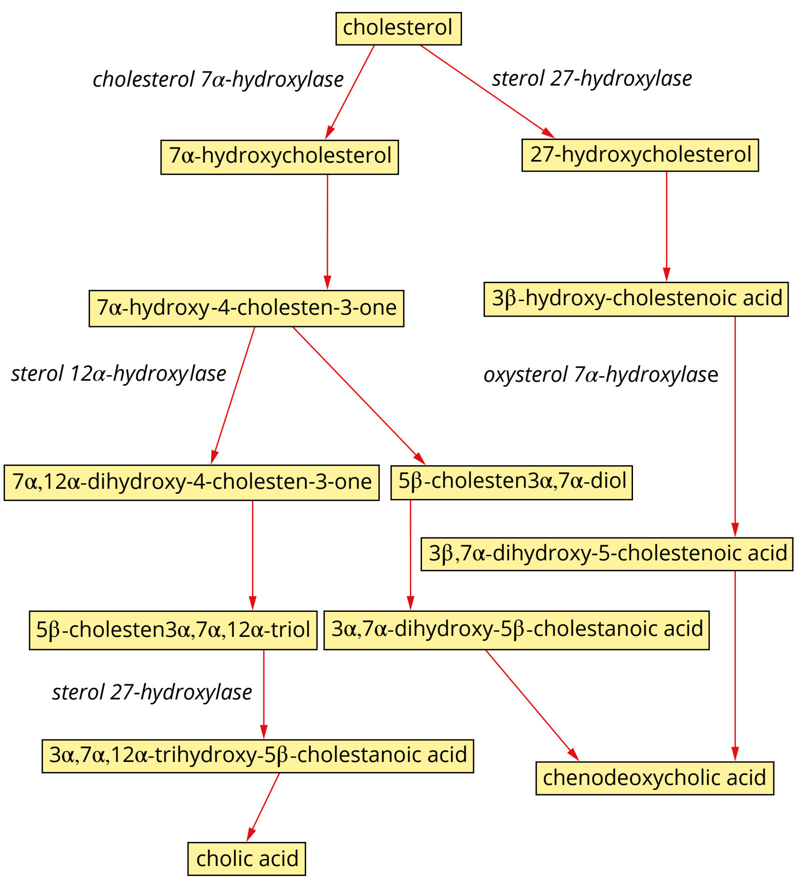
35 Bile acids are processed in the liver to form bile salts. Bile salts are used in the small intestine to mechanically break down fats in the diet. The metabolic pathway for the formation of two bile acids is shown in the flow chart. The chart is simplified; some steps in the pathway between 3β, 7α-dihydroxy-5-cholestenoic acid and chenodeoxycholic acid are not known, nor are some of the enzymes in the pathway. It is not necessary that you understand the biochemistry; you can follow and interpret the flow chart to answer the questions.



a Why are bile acids such as cholic acid and chenodeoxycholic acid necessary in digestion?

b Can you infer any other useful role for bile?

c One enzyme used in the pathway is sterol 27-hydroxylase. If an individual was unable to make functional sterol 27-hydroxylase, would they be able to make bile acids? Explain.

d Explain whether it is likely that chenodeoxycholic acid acts as an inhibitor of sterol 27-hydroxylase.

e Suggest how sterol 27-hydroxylase can catalyse two different steps in the pathway.

MODULE 3 Biological diversity

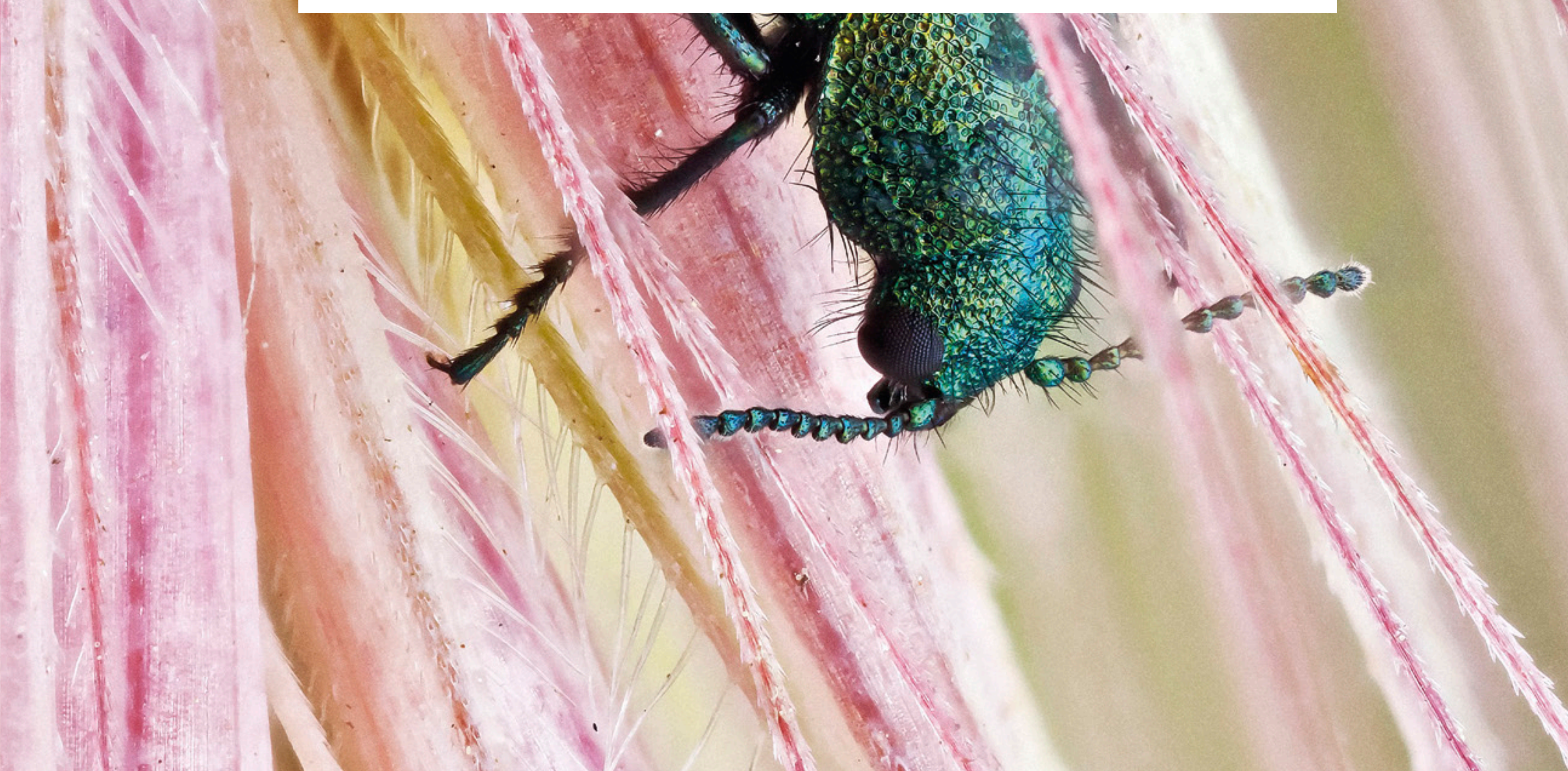
Biodiversity is important to balance Earth's ecosystems. Biodiversity can be affected slowly or quickly over time by natural selection pressures. Human impact can also affect biodiversity over a shorter time period. In this module, you will learn about the theory of evolution by natural selection and the effect of various selection pressures.

Monitoring biodiversity is key to being able to predict future change. Monitoring, including the monitoring of abiotic factors in the environment, enables ecologists to design strategies to reduce the effects of adverse biological change. You will investigate adaptations of organisms that increase the organism's ability to survive in their environment.

Outcomes

By the end of this module you will be able to:

- develop and evaluate questions and hypotheses for scientific investigation BIO11-1
- design and evaluate investigations in order to obtain primary and secondary data and information BIO11-2
- communicate scientific understanding using suitable language and terminology for a specific audience or purpose BIO11-7
- describe biological diversity by explaining the relationships between a range of organisms in terms of specialisation for selected habitats and evolution of species BIO11-10



CHAPTER

07 Effects of the environment on organisms

This chapter examines how environmental pressures promote a change in species diversity and abundance. You will investigate the abiotic and biotic factors in ecosystems and the selection pressures these factors place on organisms. This chapter will also explore the changes in populations over time due to selection pressures, such as the impact of introduced species on Australia's native flora and fauna.

Content

INQUIRY QUESTION

How do environmental pressures promote a change in species diversity and abundance?

By the end of this chapter you will be able to:

- predict the effects of selection pressures on organisms in ecosystems, including (ACSBL026, ACSBL090): CCT L
  - biotic factors
  - abiotic factors
- investigate changes in a population of organisms due to selection pressures over time, for example (ACSBL002, ACSBL094): S CCT ICT L N
  - cane toads in Australia
  - prickly pear distribution in Australia

7.1 Selection pressures: abiotic factors

DS 3.1 WS 3.1

BIOLOGY INQUIRY CCT ICT L

Environmental links

How do environmental pressures promote a change in species diversity and abundance?

COLLECT THIS...

- large piece of paper
- coloured pencils and pens
- tablet or computer to access the internet

DO THIS...

1 As a class, write the following environmental factors on a large piece of paper (scattered):
   - sunlight
   - soil
   - rain
   - eucalypt tree
   - native grasses
   - kangaroo
   - termite
   - magpie
   - wombat
   - dingo

2 Working in pairs, select a factor to research. Each group should have a separate factor.

3 Take 10 minutes to research your selected factor. Take note of how the selected factor interacts with the others. For example, 'How does the eucalypt tree interact with sunlight, soil and termites?' You will present this information to the class.

4 When the class comes together around the large sheet of paper, each pair must select a different coloured pen/pencil and draw a line from their selected factor to every factor it interacts with. Explain to the class as the line is drawn how the factor affects, or is affected by, the other factor.

RECORD THIS...

Describe how the biotic (living) and abiotic (non-living) factors interact.

Present the relationships between each of the biotic and abiotic factors in a diagram.

REFLECT ON THIS...

What are the biotic and abiotic factors in this environment?

How do these factors affect the survival of living organisms in the environment?

How do environmental pressures promote a change in species diversity and abundance?

Organisms do not live in isolation, but interact with **biotic** and **abiotic** factors in their environment. In other words, they interact both with each other and with their physical surroundings (Figure 7.1.1).

To live in a particular **habitat**, an organism must have access to the basic requirements necessary for growth and reproduction. These requirements are usually met by the organism's environment, which consists of:

- abiotic factors—the non-living components of an environment, such as temperature, light and chemical components (e.g. pH, water, gases, soil minerals)
- biotic factors—the living components of an environment, such as bacteria, fungi, plants and animals.

FIGURE 7.1.1 A hawksbill sea turtle (*Eretmochelys imbricata*) interacts with both biotic and abiotic factors in the Great Barrier Reef ecosystem.

The adaptations of organisms enable them to overcome challenges in their environment, such as cold temperatures, excess salinity, lack of water and the threat of **predators**. All organisms face pressures from biotic and abiotic factors in their environment. These are known as **selection pressures**.

Selection pressures are all the biotic and abiotic factors in an organism's environment that affect the individual's behaviour, survival and reproduction.

SELECTION PRESSURES DRIVE EVOLUTION

In every environment, certain organisms will have characteristics that are better suited to specific environmental conditions and give them a survival benefit over other individuals. These organisms are more likely to successfully reproduce under the environmental conditions, passing on their beneficial traits to their offspring. Those organisms that are less suited to the specific conditions are less likely to survive or successfully reproduce, and their genes will not be passed onto the next generation. Therefore, environmental selection pressures drive evolutionary change. Individuals that are well suited to the environment will have higher rates of reproduction and survival, passing on their well-adapted traits to their offspring. This process is called evolution by **natural selection** and is examined in Chapters 8, 9 and 10.

Selection pressures in the environment drive evolutionary change.

SELECTION PRESSURES OF THE ABIOTIC ENVIRONMENT

Abiotic pressures are created by non-living components in the environment (e.g. snow and light). Some of these factors are favourable to an organism's survival, while some are detrimental and others neutral. For example, the Antarctic environment, with temperatures ranging between −20°C and −50°C, favours the survival of the emperor penguin (*Aptenodytes forsteri*), a **species** adapted to below-freezing temperatures (Figure 7.1.2). Wind gusts in Antarctica can reach up to 200 km/h, an abiotic factor that emperor penguins can tolerate neutrally, being neither advantaged nor disadvantaged. However, as emperor penguins mostly colonise 'fast ice' (frozen seawater located between larger islands), rising global temperatures due to climate change and expected melting of ice are detrimental abiotic factors.

Abiotic factors belong to the **atmosphere**, **lithosphere** and **hydrosphere**, and create unique selection pressures for organisms as these three spheres interact. The atmosphere is the layer of gases that surround Earth. The lithosphere is the outside layers of Earth, including the crust and upper mantle. The hydrosphere is all the liquid on Earth, including the oceans, rivers, lakes and ice.

FIGURE 7.1.2 Adult and juvenile emperor penguins (*Aptenodytes forsteri*) are adapted to the freezing abiotic environment of Antarctica.

Light

Radiation that reaches Earth from the Sun is known as solar energy. Due to the shape of Earth, solar energy is spread unevenly across the planet's surface. The amount of solar energy an environment receives changes with latitude, season and time of day. For example, environments that lie between 30°N and 30°S of the equator receive the greatest amount of solar radiation, and as a result generally have very dry climates.

Plants, as well as some bacteria and protists, use solar energy for photosynthesis. This process produces oxygen used by aerobic organisms, and plays a critical role in food chains and food webs.

Light also affects many plant and animal behaviours and characteristics. Light levels can affect a plant's root growth, promote leaf expansion, and determine pigment systems, such as chlorophyll and phytochrome. In animals, light can affect a species' growth, colouration, migration, reproduction, metabolism and circadian rhythms. For example, humans and other diurnal animals are most active during daylight hours, whereas nocturnal species such as possums are most active at night (Figure 7.1.3). This behaviour in response to light conditions is due to circadian rhythms. In mammals, these rhythms are controlled by the brain's hypothalamus.

FIGURE 7.1.3 Leadbeater's possum (*Gymnobelideus leadbeateri*) is a nocturnal species that carries out most activities at night.

Temperature

As a result of solar radiation distribution across Earth's surface, as well as variation in climate, microclimate and weather, temperatures differ between environments.

The effect of environmental temperature on an organism is clearly demonstrated in the case of **dormancy**, a state in which an organism's growth, development and activity temporarily slows, or stops, to conserve energy. Dormancy generally occurs when environmental conditions are not favourable for the organism to use energy. Animals can exhibit short-term dormancy, known as daily torpor, or sustained dormancy, known as hibernation. For example, birds exhibit daily torpor by allowing their body temperatures to drop at night when temperatures are cooler, while species such as the black bear can drop their metabolic rate for several months during the coldest part of the year.

FIGURE 7.1.4 The Arctic ground squirrel (*Spermophilus parryii*) has the ability to lower its body temperature to below freezing while hibernating in the Arctic tundra's winter months.

Arctic ground squirrels (*Spermophilus parryii*) respond to below-freezing temperatures in the Arctic tundra by entering a state of hibernation for the 7–8 months of winter (Figure 7.1.4). While most hibernating individuals lower their body temperature significantly, the Arctic ground squirrel takes this to an extreme by lowering its body temperature to sub-zero. The Arctic ground squirrel is the only warm-blooded mammal known to have this ability. The squirrel is thought to dehydrate its body, removing up to 70% of all fluid before hibernation. Without this additional body fluid, ice cannot form internally and the squirrel can safely exit hibernation when the temperature begins to rise again.

You will learn more about behavioural adaptations in Chapter 8.

GO TO ➤ Section 8.3 page 360

In plants, the hormone abscisic acid is responsible for the establishment and maintenance of dormancy. For example, many boreal plant species (plants adapted to subarctic regions in the Northern Hemisphere) exhibit bud dormancy during the winter months when growth is not favourable. The environmental temperature also affects the germination of plant seeds. For example, the Australian banksia species, *Banksia elegans*, requires at least two minutes in 500°C temperatures to melt the resin on its pods and open the seed follicles to release its seeds for germination (Figure 7.1.5).

FIGURE 7.1.5 *Banksia* seedpods open following the extreme heat of a bushfire, allowing seeds to release and germinate.

BIOFILE S

Evolution in action: the yellow-bellied three-toed skink

The New South Wales native yellow-bellied three-toed skink (*Saiphos equalis*) is an example of adaptation and evolution in response to abiotic factors (Figure 7.1.6).

In warmer coastal regions, the skink reproduces by laying eggs. But in cooler mountain environments, the skinks give birth to live young in thin, transparent membranes (remnants of their ancestors' leathery shells). In colder environments, the mother's warmer body temperature is needed to protect her developing young, while in warmer environments, the young can develop in eggs outside the mother's body, reducing the mother's energetic cost.

FIGURE 7.1.6 An adult female yellow-bellied three-toed skink (*Saiphos equalis*) carrying embryos developing inside her body

Weather

Short-term variation in atmospheric conditions, such as temperature, solar radiation, wind, moisture and atmospheric pressure, change the physical environment and can affect the growth, behaviour and reproduction of organisms. This can be seen in a garden, when plant leaves wilt after several days of low rainfall and high temperatures. In the animal kingdom, researchers have discovered that birds can predict changes in weather using their 'internal barometer', which senses subtle changes in air pressure. This affects the birds' behaviour, such as flight patterns and feeding (Figure 7.1.7).

FIGURE 7.1.7 The 'internal barometer' of birds allows them to detect subtle changes in air pressure, allowing them to change their flight path if necessary.

Water

While a great amount of water exists on Earth, not all water is readily accessible for an organism's needs. The availability of water in an organism's physical environment will depend on factors such as rainfall, the presence of fresh or salt water, whether water is 'locked' in glaciers, and the amount of water vapour in the air (humidity). Plants and animals have a wide range of structural, physiological and behavioural adaptations to overcome changes in water availability in their environment. These adaptations are examined in Chapter 8.

Aquatic environments are some of the most complex and dynamic ecosystems on Earth. These environments are shaped by many factors, including:

- lithospheric elements, such as the shape of the surrounding landscape, processes of erosion, transportation and deposition, as well as sediments and suspended particles in the water
- energy, in the form of waves and tidal movements
- water chemistry, including fluctuations in oxygen levels, and freshwater versus saltwater environments
- water physics, including factors of specific gravity, heat capacity, turbidity, light penetration and upwelling.

Estuaries are an example of a complex aquatic environment, where marine saltwater is diluted by freshwater where the river meets the sea (Figure 7.1.8). This environment has high salt levels and waterlogged land. Highly specialised organisms, such as mangroves, have evolved adaptations to tolerate the fluctuating conditions of estuaries.

FIGURE 7.1.8 Estuaries are unique aquatic environments with high salt levels and waterlogged land. Mangrove plants have adapted to cope with the fluctuations in freshwater and saltwater in estuarine ecosystems.

Shelter

Shelter provides both plants and animals with protection from weather and predators, as well as providing space for growth, development and social activity. Shelter can be formed by biotic elements in the environment, such as a tree providing shade for a lion, or can be abiotic, such as a wombat sheltering in a burrow (Figure 7.1.9).

FIGURE 7.1.9 A southern hairy-nosed wombat (*Lasiorhinus latifrons*) emerges from a burrow.

Topography

Variation in **topography** (the shape of the land) affects water runoff and soil type, and can create microclimates within an environment. For example, **aspect** (the direction a slope faces) causes variation in the amount of sunlight received by an area of land. In the Southern Hemisphere, slopes with a southerly aspect generally have colder conditions and often receive harsher winds.

As well as aspect, organisms can also be affected by **altitude**, which is the height of a land mass above sea level. As altitude increases, air pressure and temperature decrease, as well as the amount of readily available oxygen. The purple copper butterfly (*Paralucia spinifera*) inhabits the central tablelands of New South Wales and will only tolerate altitudes greater than 900 m. It feeds exclusively on the blackthorn tree (*Bursaria spinosa*), which occurs in this environment and elsewhere in south-eastern Australia (Figure 7.1.10).

FIGURE 7.1.10 The purple copper butterfly (*Paralucia spinifera*) native to the New South Wales Central Tablelands inhabits high altitudes. This species is a specialist, only feeding on one species of blackthorn (*Bursaria spinosa*).

A critical component of **terrestrial** landscapes is soil. Soil is essential for the exchange of gases, nutrients and water, and for structural stability in terrestrial plants. Soil formation, type and quality are determined by topography, climate, aspect, and the geological or organic material the soil was formed from.

Chemical components

The abiotic environment of an organism includes chemicals essential for ecosystem functioning. Chemical components such as trace elements, heavy metals and pH vary within and between environments. For example, the human stomach is a naturally highly acidic (low pH) environment. Low pH is required to help activate digestion, break down food and kill bacteria and parasites. The bacteria *Helicobacter pylori* can withstand the highly acidic environment of the human stomach, penetrate the stomach lining and cause ulcers.

The physical environment also involves processes such as nutrient cycles, where essential elements are used, moved and recycled through an ecosystem. Naturally occurring elements, such as carbon, oxygen, hydrogen, phosphorus and nitrogen, are crucial for individual and species survival. For example, nitrogen is harnessed from the atmosphere, lithosphere and oceans, and converted to accessible forms to be used for protein synthesis in living organisms. These nutrient cycles involve biological, geological and chemical components, and are known as **biogeochemical cycles**.

Abiotic factors determine the distribution of organisms: that is, where organisms can survive and reproduce.

ORGANISM TOLERANCE

Tolerance is an organism's ability to survive within the physical conditions of an environment. Every organism has a particular range of conditions in which it can survive. This is known as their **tolerance range**. For each abiotic factor, there is an ideal range that is favourable for the growth, development, reproduction and survival of the organism. Outside its ideal range for a particular factor, an organism will experience stress. Development may be delayed, and health, reproduction and lifespan may be negatively affected. At a certain point outside the ideal range, the organism will die. For example, a particular species may survive between temperatures of 10–40°C, but its ideal temperature for optimum health and reproduction may be 25–30°C. At temperatures below 10°C or above 40°C, death is likely.

Bacteria are particularly susceptible to temperature ranges. For example, while the *Salmonella* genus of bacteria can survive between 5.2–46.2°C, its ideal temperature for growth and reproduction is 35–43°C (Figure 7.1.11). Meats such as chicken, which often carry the *Salmonella* bacteria, must be cooked to temperatures over 46.2°C and stored at temperatures below 5.2°C to kill the bacteria and avoid infections that lead to gastroenteritis (food poisoning).

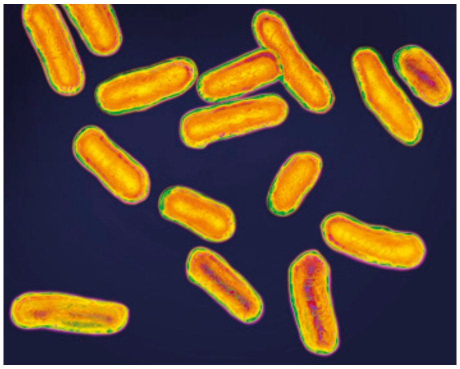


FIGURE 7.1.11 *Salmonella* bacteria can survive between 5.2–46.2°C and are a common cause of food-borne illness, such as gastroenteritis, due to improper cooking, handling or storage of products such as chicken and eggs.

Organisms with a wide range of tolerance are generally widely distributed in an environment, whereas those with narrow tolerance ranges have a restricted distribution. When an organism moves outside its tolerance limits, it can no longer survive. An example of an organism with a very narrow tolerance range is the photosynthetic algae called zooxanthellae, which inhabits coral tissues (Figure 7.1.12). Zooxanthellae are not widely distributed, being limited to shallow tropical and subtropical waters between latitudes of 30°N and 30°S. They have an optimum temperature range of 16–18°C. The waters become uninhabitable for zooxanthellae when temperatures drop below 16°C for more than a few weeks at a time, or when temperatures rise by more than 1–2°C for more than a few days or weeks.

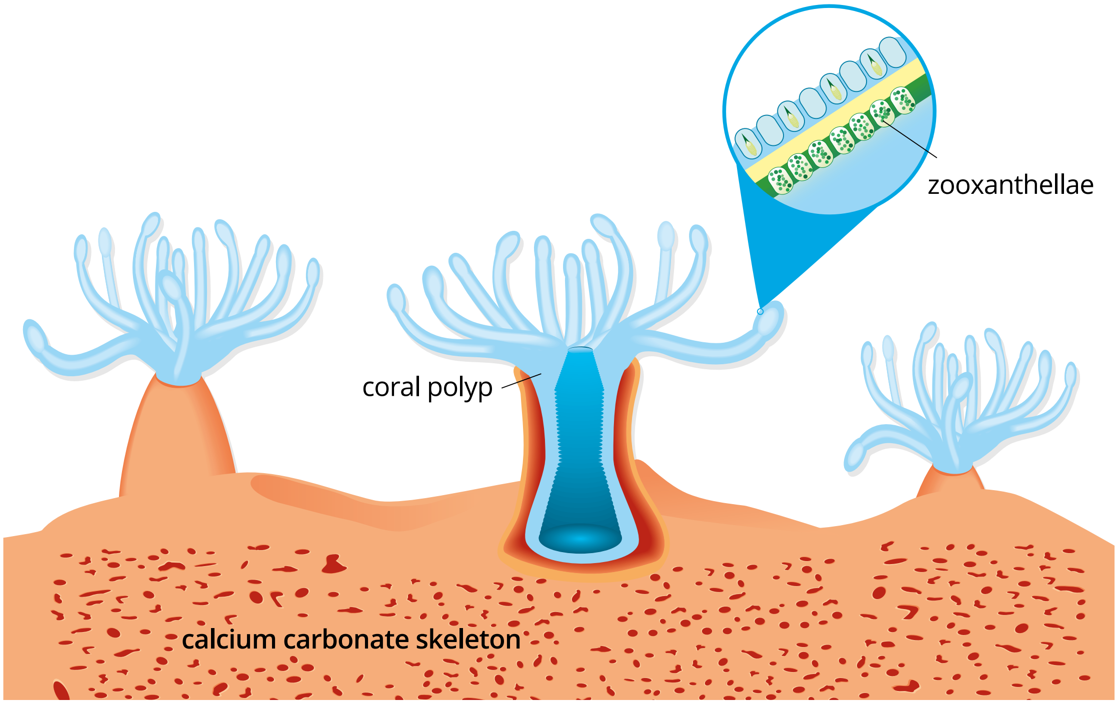


FIGURE 7.1.12 Zooxanthellae are photosynthetic algae that inhabit coral tissues and require a specific temperature range for survival.

HUMAN IMPACTS ON THE ABIOTIC ENVIRONMENT

Human activities, such as industry and urban development, affect the atmosphere, hydrosphere and lithosphere, and in turn place new or altered selection pressures on organisms. For example, the atmosphere has been heavily polluted, leading to climate change, thinning of the ozone layer, and decreased sunlight penetration. Similarly, the lithosphere has been gradually polluted and altered, which has increased runoff, salinity and erosion. The hydrosphere also faces new challenges, such as changes in water pH, reduced dissolved gases, rising sea levels, and pollution with toxic chemicals and litter.

These human-induced effects alter the abiotic selection pressures already placed on organisms, as well as introducing new selection pressures. For example, increased levels of carbon dioxide in the atmosphere causing a rise in global temperatures places exaggerated selection pressures on the corals of the Great Barrier Reef.

As mentioned above, corals have a close partnership with photosynthetic zooxanthellae, which give the coral their brilliant colours and provide nutrients. In return, the coral provides shelter for the zooxanthellae. The human-induced rise in global temperatures is placing stress on corals and zooxanthellae, causing the corals to eject the zooxanthellae. Without the zooxanthellae, the coral lose their colour, causing coral bleaching (Figure 7.1.13).

The relationship between coral and zooxanthellae is explored further in Chapter 11.

GO TO ➤ Section 11.1 page 501

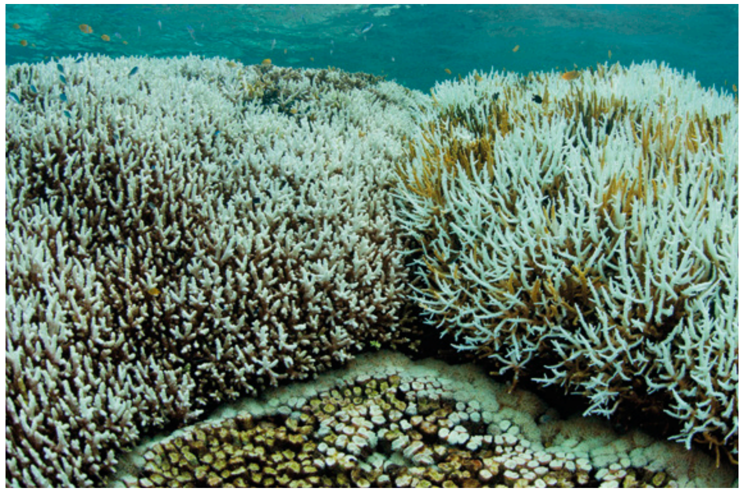


FIGURE 7.1.13 Coral on the Great Barrier Reef showing signs of coral bleaching. The photosynthetic algae called zooxanthellae live inside the coral, giving the corals their brilliant colours. Coral bleaching occurs when the coral expels the photosynthetic algae from their tissues due to stress. It is becoming more common with rising ocean temperatures.

Humans are rapidly altering the abiotic and biotic factors in many environments. These environmental changes alter the selection pressures organisms experience and are occurring at a rate faster than many species can adapt to.

BIOLOGY IN ACTION CC S

Saving the mountain pygmy possum

The mountain pygmy possum (*Burramys parvus*) is a small, ground-dwelling possum that inhabits the alpine and subalpine environments of south-eastern Australia, including Kosciusko National Park. The mountain pygmy possum is the only Australian marsupial that hibernates for long periods during winter, emerging in spring to breed. Biologists have observed that climate change poses the greatest ongoing threat to the possum, particularly as winter seasons shorten and climatic temperatures of the possum's habitat rise.

Possums feed on migratory Bogong moths (*Agrotis infusa*) after hibernation. As snow begins to melt earlier due to higher temperatures, possums awaken from their hibernation before the moths arrive and therefore must compete with other mammals for alternative food sources. Also, while the extreme cold temperatures once kept introduced species such as feral cats out of the mountain pygmy possums' habitat, biologists have identified these predators entering the now-warmer environments.

Conservation strategies have been established to protect the mountain pygmy possum, with captive breeding programs established in New South Wales and Victoria (Figure 7.1.14). Scientists are also looking into the fossil record to understand how ancestors of the mountain pygmy possum previously adapted to a changing climate.

FIGURE 7.1.14 A biologist holds a mountain pygmy possum at Healesville Sanctuary in Victoria.

7.1 Review

SUMMARY

- Organisms are in constant interaction with their environment, which includes biotic and abiotic factors.
- Abiotic factors include:
  - light
  - temperature
  - weather
  - water
  - shelter
  - topography
  - chemical components.
- Selection pressures in the environment affect an organism's behaviour, survival and reproduction.
- The atmosphere, hydrosphere and lithosphere interact to create a tangible environment that influences the behaviour, development and distribution of living organisms.
- An organism's ability to survive depends upon the physical limits it can tolerate in its environment. This is known as an organism's tolerance range.
- Selection pressures drive evolution by determining which organisms survive and reproduce to pass on their beneficial traits to the next generation.
- Human activities impact the abiotic environment in many ways, such as increasing atmospheric carbon dioxide, polluting water bodies and altering soil structure.
- Human activities can place new or altered selection pressures on organisms.
- If the environment and selection pressures change rapidly, many species cannot adapt and may become extinct.

KEY QUESTIONS

1 Distinguish between abiotic and biotic factors of an environment.

2 List two types of abiotic factors found in the environment and give an example of how each can affect an organism.

3 Define 'selection pressure'.

4 Provide an example of the extent to which temperature can affect an animal's behaviour and survival.

5 Explain how abiotic factors and organism tolerance are related.

6 Why should meats such as chicken be cooked above temperatures of 46.2°C?

7 Provide an example of human-induced abiotic selection pressures.

7.2 Selection pressures: biotic factors

While organisms are under selection pressures from abiotic factors in their environment, they also experience selection pressures from biotic factors. In an ecosystem, organisms interact and depend upon one another for survival. They influence one another by being part of each other's environment. In this section, you will learn about the biotic factors in an ecosystem and how these factors place selection pressures on organisms in their environment.

FIGURE 7.2.1 The Queensland umbrella tree (*Schefflera actinophylla*) is an individual in an ecosystem.

ORGANISING THE ENVIRONMENT

Environments can be studied at different levels. The biological levels of organisation listed below follow a structured hierarchy of living things.

Individuals

An **individual** is a single organism, such as one animal, plant, fungus or unicellular organism. A single Queensland umbrella tree (*Schefflera actinophylla*) is an example of an individual (Figure 7.2.1). This tree usually has many flowers, which produce large amounts of nectar: an important food source for many animals.

> A species is a group of organisms that can reproduce. A group of individuals of the same species that live together is called a population.

Populations

A **population** is a group of organisms of the same species, living together in a defined geographic area. The spectacled flying fox (*Pteropus conspicillatus*), also known as a fruit bat, lives in colonies that roost together and interact (Figure 7.2.2). The fruit bats in a colony could be described as a population.

FIGURE 7.2.2 A colony of spectacled flying foxes (*Pteropus conspicillatus*) is a population that lives in the Daintree Rainforest, Queensland, and feeds from the nectar of the umbrella tree.

FIGURE 7.2.3 Bennett's tree kangaroos (*Dendrolagus bennettianus*) live in the canopy of rainforest trees. They are part of a community in the Daintree Rainforest, Queensland, which includes umbrella trees and spectacled flying foxes.

Communities

A **community** is an ecological grouping of different species that live together and interact. Many species rely on the Queensland umbrella tree for the nectar it produces, including the spectacled flying fox, various species of bird and the Bennett's tree kangaroo (*Dendrolagus bennettianus*) (Figure 7.2.3). The diverse species living in and feeding in a population of umbrella trees could be considered a community.

Ecosystems

An **ecosystem** is a system formed by communities of organisms interacting with one another and their physical surroundings. To be defined as an ecosystem, a system must be self-sustaining. This means that it can be maintained long term, largely without inputs from outside the system.

The Queensland umbrella tree, spectacled flying fox and Bennett's tree kangaroo can all be found in the Daintree Rainforest in Queensland. The Daintree Rainforest is regarded as the most complex ecosystem in Australia. It is a distinct area with many different species (high **biodiversity**) that interact and thrive together (Figure 7.2.4).

FIGURE 7.2.4 The Daintree Rainforest is part of a World Heritage Area. It is a complex ecosystem that includes a diverse range of species.

FIGURE 7.2.5 The Mallee ecosystem is characterised by multi-stemmed mallee eucalypts, such as the white mallee (*Eucalyptus dumosa*).

Ecosystems can be almost any size. An ecosystem can be as small as a dead tree trunk, or it can be large, like the Victorian Mallee (Figure 7.2.5).

Ecosystems also vary in complexity. A tropical forest is the most complex land ecosystem and contains the greatest number of species. A desert ecosystem is one of the simplest, because it has fewer different species. Cities and towns are urban ecosystems.

Ecosystems can also be found within ecosystems. For example, rock pools along the seashore are part of larger marine ecosystems, but they can also be studied as small ecosystems (Figure 7.2.6).

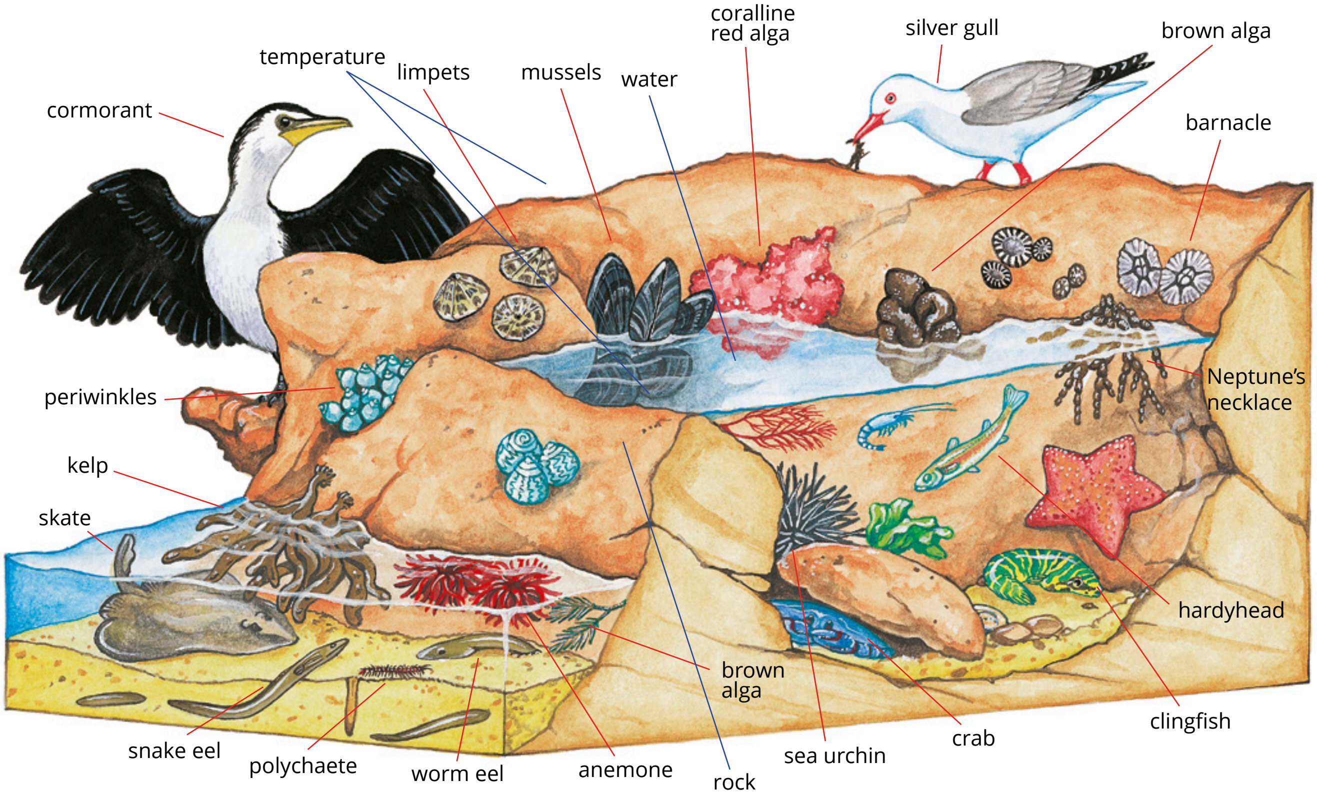


FIGURE 7.2.6 Rock pool ecosystems provide habitat for many different organisms whose survival depends on tides. An incoming tide brings cool, clean water, food and organisms. When the tide goes out, it leaves behind a calm pool that warms in sunlight. The red lines indicate biotic factors in the ecosystem and the blue lines indicate abiotic factors.

Biomes

A **biome** is a group of communities that have similar structures and habitats extending over a large area; for example, a rainforest biome, a grassland biome or coral reef biome. The Daintree Rainforest is a part of the tropical rainforest biome. The tropical rainforest biome is close to the equator and experiences high temperatures and rainfall (Figure 7.2.7).

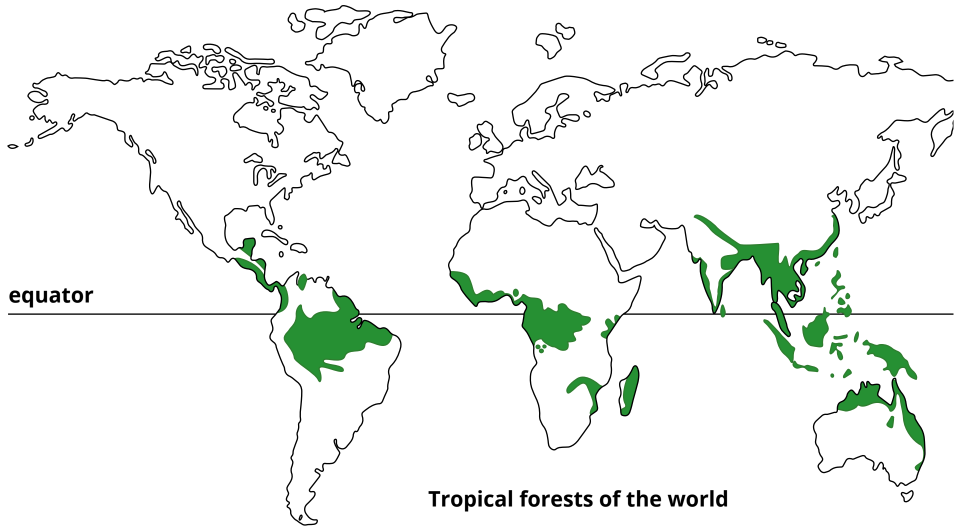


FIGURE 7.2.7 The tropical rainforest biome (shown in green) is found close to the equator. The Daintree Rainforest is part of this biome.

Biosphere

The largest and most complex ecosystem of all is the **biosphere**, which is the sum of all ecosystems on Earth (Figure 7.2.8). The biosphere includes all those parts of Earth that are inhabited by living organisms, including oceans, rivers, lakes (hydrosphere), soil and rocks (lithosphere) and air (atmosphere). The biosphere occupies a thin layer of atmosphere, the hydrosphere, and a thin layer of lithosphere (Figure 7.2.9).

FIGURE 7.2.8 The biosphere is the global ecosystem. It consists of smaller interlinked ecosystems and larger biomes.

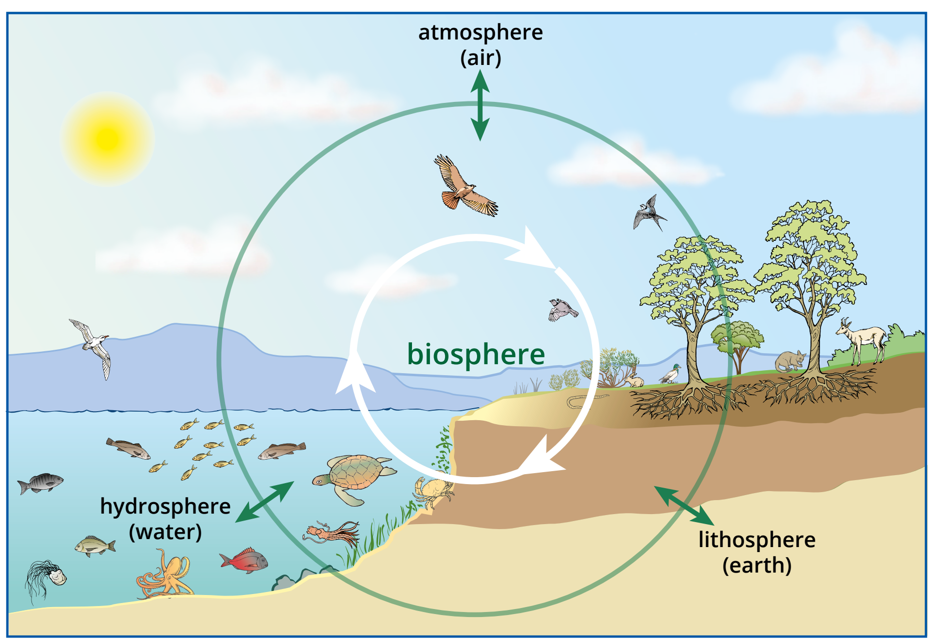


FIGURE 7.2.9 The biosphere is the portion of Earth inhabited by living things. It occupies parts of the atmosphere, hydrosphere and lithosphere.

HABITAT

To study an organism, you first have to know where to find it. The type of place where an organism lives is its habitat. For example, the habitat of rock orchids, as the names suggests, is rocky outcrops in forests. The habitat of a water lily is lakes and ponds. The bush rat lives in forests, while the swamp rat lives mainly in grasslands and heathlands close to water. The European house sparrow, introduced into Australia, makes its home in towns and cities. Different habitats support different species (Figure 7.2.10).

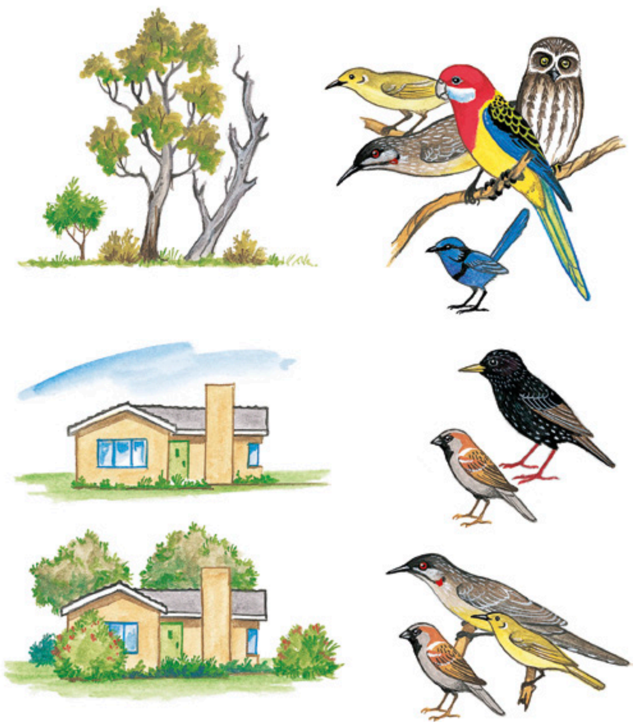


FIGURE 7.2.10 The bird community in a new suburb (centre) consists of sparrows and few native species. Gardens that include native plants provide habitat for a greater variety of native birds.

Some organisms live in only one type of habitat. In Victoria, a species of snow daisy is found only in the mountains of the Snowy Range and near Mount Buller. The Sydney rock oyster, although found at many locations along the east coast of Australia, lives along the shore in a narrow band between high and low tide.

Other organisms live in a greater range of habitats. Australian flying foxes inhabit forests, paperbark swamps and mangroves from Queensland to Victoria (Figure 7.2.11). Some organisms move from one habitat to another according to seasonal changes. For example, pelicans move inland from their coastal habitat to take advantage of wetlands that form during times of rain and flood.

Microhabitat

Within a habitat are smaller areas known as **microhabitats**. A microhabitat could be a burrow, a tree canopy or even the inside of other organisms.

In a microhabitat, an organism experiences a slightly different environment than the overall habitat, such as a lower temperature, more moisture, less sunlight or more humidity. This variation in environmental conditions can be essential for the organism to survive.

The moist trunk of the tree fern (*Dicksonia antarctica*) in a wet forest is the microhabitat of many mosses, liverworts, ferns, fungi, spiders and insects. The soft trunk of the tree fern is shaded by its umbrella of large fern leaves, and can absorb and hold a lot of water (Figure 7.2.12). The tree fern trunk is a different microhabitat from the trunk of trees such as silver wattles (*Acacia dealbata*) in the same forest habitat (Figure 7.2.13).

FIGURE 7.2.11 Many species of flying foxes inhabit forest habitats in eastern Australia.

FIGURE 7.2.12 The trunk of the tree fern (*Dicksonia antarctica*) is a microhabitat for many species.

FIGURE 7.2.13 The trunk of a silver wattle (*Acacia dealbata*) is not the same microhabitat as the trunk of a tree fern.

ⓘ Habitats and microhabitats are specific parts of an ecosystem that populations of organisms use for shelter, obtaining resources, breeding and raising offspring.

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BIOFILE ICT S

Biosphere 2

The Biosphere 2 research facility in the USA is a science research facility covering 160 000 m^2 (Figure 7.2.14). It was designed to be a self-contained ecological system, with different types of biomes closed off from the outside world. Scientists have used Biosphere 2 to study the interactions between humans and nature, the impact of climate change, and even space colonisation.

FIGURE 7.2.14 The Biosphere 2 research facility in Arizona, USA

ⓘ Keystone species are species that play critical roles in the structure and functioning of an ecosystem.

FIGURE 7.2.16 A cluster of sea stars (*Pisaster ochraceus*): the predator species first termed a keystone species

CHANGES TO A SPECIES WITHIN AN ECOSYSTEM

Species are interconnected in many ways within an ecosystem. When a change occurs to one species, other species and sometimes even the entire ecosystem are affected.

Food webs are one way in which species are interconnected. The complexity of a food web provides stability in an ecosystem. In a simple food web, the loss of one species would have a disastrous effect on the other organisms. In a complex food web, the loss of one species has less effect, since alternative food sources are often available. Food chains and food webs are examined further in Chapter 11.

Changes to a keystone species

Some species in an ecosystem can be identified as **keystone species**. A keystone species plays a critical role in maintaining the structure of an ecosystem (Figure 7.2.15). When a keystone species is removed, the ecosystem becomes much less stable, and its structure changes. At times like this, the selection pressures in an ecosystem are likely to be significant, with consequences for both the **diversity** and the **abundance** of species.

FIGURE 7.2.15 A keystone is the central stone that supports the arch structure in a stone archway. A keystone species is so named because it maintains the structure of its ecosystem in a similar way.

The term keystone species was first applied during a study of food webs in rock pools. The carnivorous sea star *Pisaster ochraceus* (Figure 7.2.16) was identified as the top predator in the rock pools. As an experiment, all the *Pisaster* sea stars were removed from one rock pool, with a second rock pool nearby left undisturbed as a control. In the rock pool that the sea stars were removed from, the remaining species competed with each other to occupy the extra space and to use the additional resources made available. Two types of barnacles and a mussel species began to dominate. The barnacles and mussels consumed so much of the limpets' food source (algae) that the limpet population decreased. Within a year, the number of limpet species decreased from 15 to 8. In the control rock pool, there was no change in species number or distribution. Because these significant changes in the ecosystem resulted from the removal of one species—the sea star—it was called a keystone species.

This experiment showed the significant impact of removing a keystone species from an ecosystem. Many other species have since been identified as keystone species. Because of their important role in the structure and functioning of ecosystems, keystone species are frequently targeted for **conservation** efforts.

The number of the great white sharks (*Carcharodon carcharias*) (Figure 7.2.17) has been declining, mostly because they are caught in fishing nets or hunted. This has had far-reaching effects on marine ecosystems. The great white shark is a predator at the top of the food chain, keeping the populations of fish, seal and sea lion species they consume in check, as well as the animals that those species consume. The great white shark is a keystone species that helps maintain the stability of marine food chains.

FIGURE 7.2.17 The great white shark (*Carcharodon carcharias*) is an important predator and a keystone species in marine ecosystems.

Another well-known keystone species is the northern quoll (*Dasyurus hallucatus*), also known as the native cat (Figure 7.2.18). This species has become endangered for many reasons, including bushfires and feeding on poisonous cane toads. The quoll feeds on a large variety of foods, including fruit, insects, birds, mammals and reptiles. Through feeding, the quoll helps control the numbers of its **prey** species. With the quoll's decline, the delicate balance of those populations is being disrupted.

FIGURE 7.2.18 The northern quoll (*Dasyurus hallucatus*) is an endangered keystone species of carnivorous marsupial found in Queensland, the Northern Territory and Western Australia.

Keystone species and habitat

Some species are keystone species because they maintain important habitats within an ecosystem. For example, elephants preserve the grasslands of African savannas by eating any young trees that grow (Figure 7.2.19). Without the elephants, the savannas would be invaded by trees and shrubs and eventually become forests or shrublands. The many smaller grazing herbivores, such as wildebeests and zebras, would starve.

FIGURE 7.2.19 Elephants are a keystone species in African savannas because they maintain the grassland ecosystem.

HUMAN IMPACTS ON THE BIOTIC ENVIRONMENT

The impact of human activities on the biotic environment also adds to selection pressures, both directly and indirectly. For example, trawling certain fish species can reduce their abundance, which decreases food availability for higher predators, such as sharks, indirectly affecting shark populations (Figure 7.2.20). Humans can directly place selection pressures on organisms through processes such as **artificial selection**. Artificial selection involves selectively breeding organisms with specific traits to increase the number of offspring with these desired traits. Examples of artificial selection are selecting and breeding hens that lay large eggs, or developing drought-resistant crops. You will learn more about artificial selection in Chapter 9.

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By studying biological diversity and understanding how organisms function and interact, scientists can predict how species, populations, communities and ecosystems may be affected by human activities. This knowledge can be applied to help conserve environments and minimise the damage of human activities in the future.

FIGURE 7.2.20 An example of a human activity that has greatly affected biotic environments is the commercial fishing trade. The fishing industry removes fish from their food web, which can significantly affect the other species in the web.

Removing a keystone species from an ecosystem can have significant, long-term effects for other species in the ecosystem.

Human impacts on keystone species

Human activities can harm ecosystems, particularly where these activities affect a keystone species. One example is the culling of grey wolves from Yellowstone National Park in the United States (Figure 7.2.21). The wolves were originally seen as a pest, but their eradication allowed a rapid increase in the elk population, which massively overgrazed the aspen and willow plants. This led to a loss of habitat and food for many smaller species, such as beavers and songbirds, as well as stream bank erosion and water sedimentation. In 1995, grey wolves were reintroduced. The ecosystem is slowly recovering.

FIGURE 7.2.21 Grey wolves are a keystone species in the Yellowstone National Park because they keep the elk population in check.

7.2 Review

SUMMARY

- The biosphere can be organised into smaller units of individuals, populations, communities, ecosystems and biomes. This system of organisation makes it easier to study and understand biological diversity.
- An individual is a single organism, such as one microbe, one plant or one animal.
- A population is a group of organisms of the same species living in a defined geographic area.
- A community is an ecological grouping of different species that live together and interact.
- An ecosystem is a system formed by communities of organisms interacting with one another and their physical surroundings.
- A biome is a group of communities that have similar structures and habitats, extending over a large area.
- The biosphere is the sum of all ecosystems on Earth.
- A habitat is the place where an organism lives.
- Within a habitat are smaller areas known as microhabitats. An example of a microhabitat is the area under the bark of a tree.
- If there is a change to one species or if a new species is introduced, other species and sometimes the entire ecosystem are affected, because species are interconnected in their ecosystem.
- Keystone species are critical to the stability of an entire ecosystem. If they are removed, the entire ecosystem can be affected.
- Humans influence environmental selection pressures through activities such as industrial practices, land clearance, agriculture and artificial selection for food production or aesthetic value.

KEY QUESTIONS

1 What is the difference between individuals and populations?

2 Describe an ecosystem and provide an example of an ecosystem in your local area.

3 What is a microhabitat? Explain using an example.

4 Provide an example of a keystone species, and explain why keystone species are important to their environment.

5 Why are keystone species often the focus of conservation efforts?

6 Provide an example of how humans affect the biotic selection pressures in an environment.

7 Why do human activities have such far-reaching consequences for so many species? Explain your answer using an example.

7.3 Population changes

FIGURE 7.3.1 A school of anchovies swim near a whale shark (*Rhincodon typus*) to avoid predation: the whale shark only feeds on smaller animals, such as krill. Anchovies often swim in large groups of thousands of individuals, while whale sharks usually swim alone. The population sizes of these species are very different.

In theory, populations should continually increase in size as a species produces more individuals. However, this is rarely the case in an ecosystem. Instead, **population density** and size are determined by a variety of factors that influence rates of birth, **immigration** (coming into a population), **emigration** (leaving a population) and death. Population sizes also vary considerably between species (Figure 7.3.1). In this section, you will explore the selection pressures that affect the distribution, density and size of populations within an ecosystem. In particular, the introduction of the cane toad and prickly pear to Australia will be examined.

POPULATION DISTRIBUTION

Geographic distribution (or range) is all the places where a species is found. For example, emus are found only in Australia, and kiwis are found only in New Zealand. The rock orchid (*Dendrobium kingianum)* has a restricted range, because it is only found in parts of eastern Australia (Figure 7.3.2).

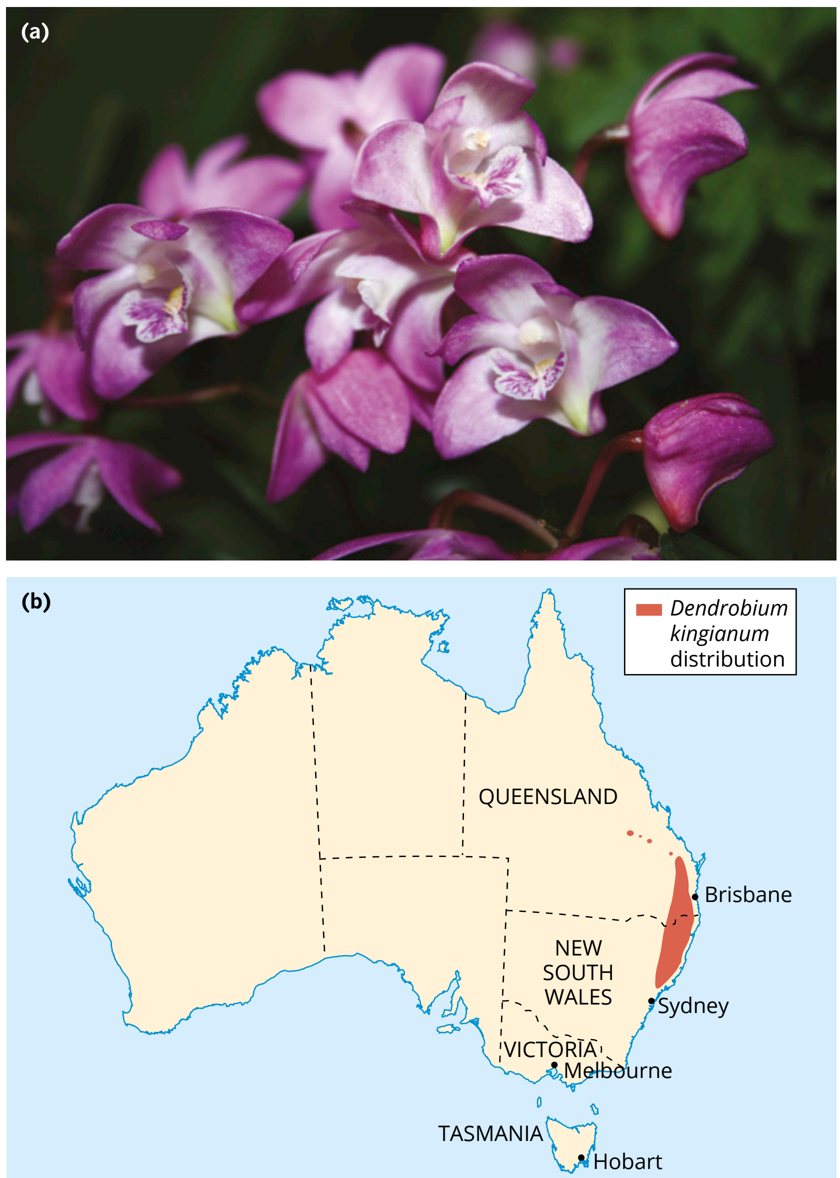

FIGURE 7.3.2 (a) The rock orchid (*Dendrobium kingianum)* and (b) its restricted geographic distribution in eastern Australia

The distribution of a population within a habitat demonstrates the spatial relationship between those individuals. There are three basic patterns of distribution: random, uniform and clumped (or clustered) (Figure 7.3.3).

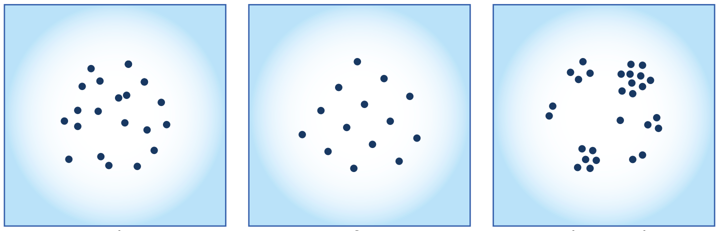

FIGURE 7.3.3 The three patterns of population distribution: random, uniform and clumped. The blue dots represent individual organisms.

FIGURE 7.3.4 South Georgia's king penguin colony demonstrates relatively uniform population distribution.

To investigate changes in population, an accurate way of measuring their distribution and abundance is required. The method used will depend on the size, mobility and location of the organism. Some populations will be easier to measure than others; organisms that are abundant, less mobile and in easily accessible locations are more likely to be accurately counted than those that are rare, mobile and difficult to access. For example, a population of *Acacia* bushes is easier to count directly than a flock of galahs in flight. The distribution pattern will also influence the method used to estimate a population's distribution and abundance.

A uniform distribution means individuals are equally spaced apart: for example, penguins on a continental ice shelf (Figure 7.3.4). A randomly distributed population arises where individuals are spaced unpredictable distances from each other. This may occur in wildflowers that have been wind dispersed as seeds (Figure 7.3.5). Clumped populations arise where individuals are clustered together: for example, lions surrounding a carcass to feed (Figure 7.3.6).

FIGURE 7.3.5 Yellow desert flowers in Bahrain display random population distribution.

FIGURE 7.3.6 Lions feeding in Masai Mara, Kenya, demonstrate a clustered population distribution.

The geographic distribution (or range) of a species is determined by abiotic and biotic selection pressures.

Factors affecting population distributions

The distribution pattern of a population may be a reflection of the physical environment, the characteristics of the species, or the behaviour of the organism. Each distribution has advantages and disadvantages. For example, clumped populations may have to compete with other individuals for local resources; however, their social setting allows for higher probability of finding a mate.

Geographic distributions may change over time. For example, humans have aided the spread of weeds and animal pests. Humans have also reduced the distribution range of species by clearing forests and interfering with other natural ecosystems.

Prickly pear introduction to Australia

FIGURE 7.3.7 The prickly pear (*Opuntia* species) invaded farmland in Australia very quickly after its introduction. It outcompeted native vegetation and became a pest for farmers. Biological control with the moth *Cactoblastis cactorum* destroyed almost all the prickly pears, and today they are rarely seen.

An example of human-induced distribution change is the prickly pear cactus (*Opuntia* species) (Figure 7.3.7). The term prickly pear includes around 10 members of the Cactaceae family native to the Americas. It is a mostly leafless plant, characterised by fleshy, spine-covered growth and large (often yellow) flowers. The prickly pear's original geographic distribution expanded when it was taken to Europe by the Spanish, and subsequently introduced to Australia by early settlers in approximately 1788. Its distribution rapidly expanded across Australia and it soon became an **invasive species**.

The prickly pear was introduced to Australia as part of the textile dye industry. A scarlet dye was produced from cochineal insects, which feed on certain species of cactus—one of which was the prickly pear. The insects were harvested on cacti and squashed to obtain the cochineal pigment (Figure 7.3.8). During the 18th century, Spain was the largest contributor to the cochineal dye industry. The scarlet dye was incredibly valuable during this time, with the colour representing wealth, power and royalty. As such, the British government wanted its own supply of this dye, especially for the colouring of its red military coats (Figure 7.3.9).

The First Fleet brought the first collection of cochineal-infested prickly pear specimens to Australia in 1788. It was not until the mid 19th century that the cochineal industry ended when synthetic dyes were introduced.

FIGURE 7.3.9 The scarlet dye produced by the cochineal beetle was used in 18th and 19th-century clothing, including the famous British military coats.

FIGURE 7.3.8 (a) Cochineal beetles clustered on a prickly pear cacti leaf, and (b) the scarlet dye produced by the cochineal insects

STUDYING POPULATION DENSITIES AND DISTRIBUTION

The density of a population is the number of individuals per unit of area or volume. For example, this might be the number of prickly pear plants in a given area of land, or the number of fish in a particular volume of water.

If it is difficult to count individuals, the size of a population can be measured in **biomass**. For example, counting blades of grass is a tedious process, so a grass population is often measured in kg per unit area (Figure 7.3.10). A small area of grass can be cut and weighed, and then this value can be used to calculate the total biomass of the population.

Biomass is an amount of organic matter. It is usually expressed as mass per unit, such as kg/m^2.

The area used to measure density might sometimes be represented by a less conventional unit. For example, the population density of plant lice can be directly counted and expressed as the number of individuals on one leaf (Figure 7.3.11).

FIGURE 7.3.10 Blades of grass would be difficult to count for a population density measurement. Instead, a sampling and calculation method can be used to estimate the population density.

FIGURE 7.3.11 The density of plant lice can be measured by counting the number of lice per leaf.

POPULATION GROWTH

The size of a population can be affected by four processes:

- births or germination (also called **natality**)
- deaths (also called **mortality**)
- immigration (organisms moving into a population from another population)
- emigration (organisms moving out of a population).

Birth and immigration introduce new individuals and thus increase the population size. Death and emigration decrease the population size. Immigration and emigration are collectively known as **migration.** These four processes determine the rate of change in a population over time (Figure 7.3.12).

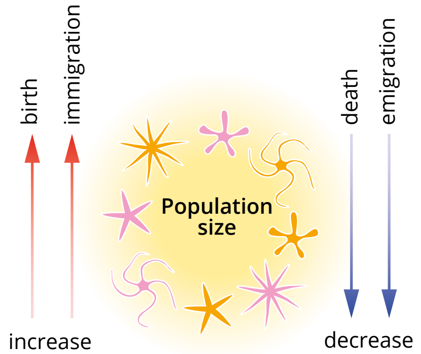

FIGURE 7.3.12 The size of a population depends on birth rate, death rate, immigration and emigration.

Exponential population growth

When populations are not limited by resources, predators or disease, they can experience continual, unlimited growth known as **exponential growth**. Because individuals continue to reproduce regardless of population size, the rate of population growth increases each generation. In nature, population growth is eventually limited by the **carrying capacity** of the environment. You will learn more about ecosystem carrying capacity and its effects on populations in Chapter 11.

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Theoretical exponential growth

Ecologists use mathematical formulae to model the theoretical growth of a population over time. The graph in Figure 7.3.13 shows a theoretical growth curve for a population in an ideal environment, which includes all the resources that an organism needs (e.g. food, water, shelter and mates for reproduction).

The graph in Figure 7.3.13 assumes that the number of immigrants equals the number of emigrants over time, meaning that the rate of overall migration is zero. Change in this population is therefore a function of births and deaths only. This type of growth is known as exponential growth. The J-shaped curve of the graph is characteristic of exponential population growth.

As long as the birth rate is higher than the death rate, a population will grow. If the birth rate remains consistently higher, then the population may grow exponentially.

Population growth, density and distribution are affected by the number of births, deaths and individuals entering and leaving the population.

Year	0	1	2	10
Size of population	100	200	400	102 400

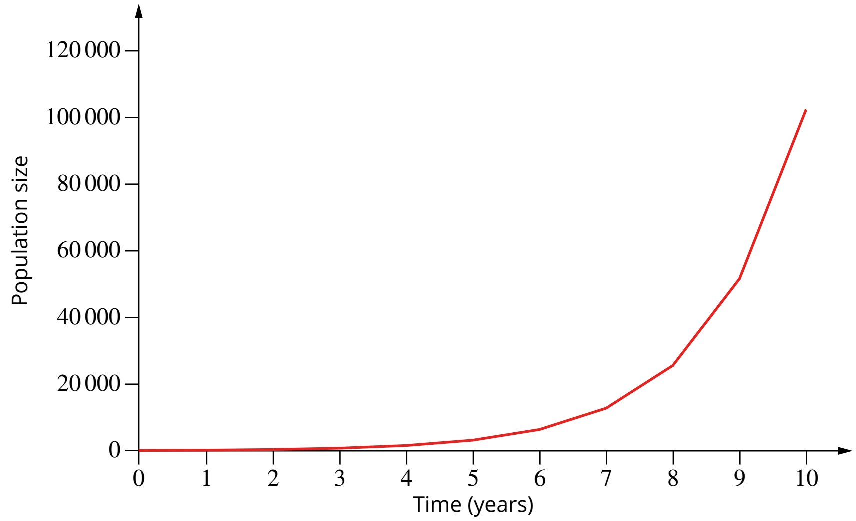


FIGURE 7.3.13 The size of a population over time (years), showing exponential population growth

FIGURE 7.3.14 The periodical cicada (genus *Magicicada*) spends most of its long life underground feeding on the roots of deciduous trees in North America.

Exponential population growth occurs if there are no factors limiting the growth of populations.

Exponential growth in real populations

Species that tend to experience exponential population growth are those that have a short generation time and give rise to large numbers of offspring. Examples of these species are bacteria, many weed species and some types of insects. In most instances, exponential population growth occurs only for relatively short periods.

Some species may experience exponential growth during certain periods of their lifecycle. Organisms that reproduce during a particular period of the year often have massive increases in their population size during this time, and decreases in population size throughout the rest of the year.

An example of this is a sea turtle. Sea turtles come ashore once a year and bury large numbers of eggs in the sand. When these hatch, the turtle population is very large. However, very few baby turtles make it safely to the water or survive predation in the ocean. Other species reproduce even less frequently.

Another example is that of periodical cicadas (genus *Magicicada*). They live underground for up to 17 years before emerging to reproduce, when the females lay hundreds of eggs in 3 or 4 weeks. The population growth at this time is explosive, but only occurs for a short time (Figure 7.3.14).

SKILLBUILDER L N

Plotting population changes

Population changes over time can be measured and analysed by conducting population counts. Population count data allows scientists to monitor and predict population changes and provides valuable information for the management and conservation of populations.

Plotting a line graph

Line graphs are a useful way to represent changes in a population over time. The independent variable is always plotted on the *x*-axis and the dependent variable is always plotted on the *y*-axis. Once the variables have been identified, the axes need to be labelled, including any units in brackets where appropriate. For example: 'number of eagles (1000s)' or 'weight of eagle chicks (g)'.

The scale of each axis needs to be determined by identifying the range of values to be represented in the graph. If the range of values is large (e.g. 0–100 000), then the intervals between the data points may need to be large to fit on the axis (e.g. 20 intervals of 5000). If the range of values is small (e.g. 0–5), then the intervals on the axis can be small (e.g. 10 intervals of 0.5). A heading above the graph that describes the data presented also needs to be included.

The values are plotted as points on the graph and a line is drawn from one point to the next (Figure 7.3.15). The slope of the line can then be interpreted to answer biological questions and predict changes in populations over time.

See Chapter 1, page 34 for more details about line graphs.

SKILLBUILDER L N

Interpreting a line graph

A line sloping downwards indicates a decrease in numbers, while a line sloping upwards indicates an increase in numbers. A steep line can represent a rapid change in the population size, and a gradual slope can represent a slow change.

The scale of the graph axes must always be considered when interpreting a graph. For example, a steep line may appear to represent rapid population change, but this may not be the case if the intervals between numbers on the *y*-axis are small or the intervals of time on the *x*-axis are large. An example of this can be seen in Figure 7.3.15. This graph appears to indicate that there have been large fluctuations in eagle numbers over the year the data was collected. However, the *y*-axis scale is only 0–12, and the steep lines only represent population changes of 3–5 individuals.

The biology of the organism being studied must also be taken into account. Reproduction rates and timing may vary greatly between months, seasons or years. Generation times and population size must also be considered. Although a population change of 3–5 individuals represented in Figure 7.3.15 doesn't seem significant, it may be in populations with very few individuals.

Potential biases and errors in the data should also be considered when interpreting a graph. The example in Figure 7.3.15 seems to indicate a small population of eagles with large fluctuations in numbers. However, the researcher conducting the count may have been sampling in an area where very few eagles fly, or may have been using equipment that made the population counts unreliable. The scale of the graph may also be incorrect; perhaps the *y*-axis should be in 100s or 1000s. Many factors need to be considered when drawing conclusions from data.

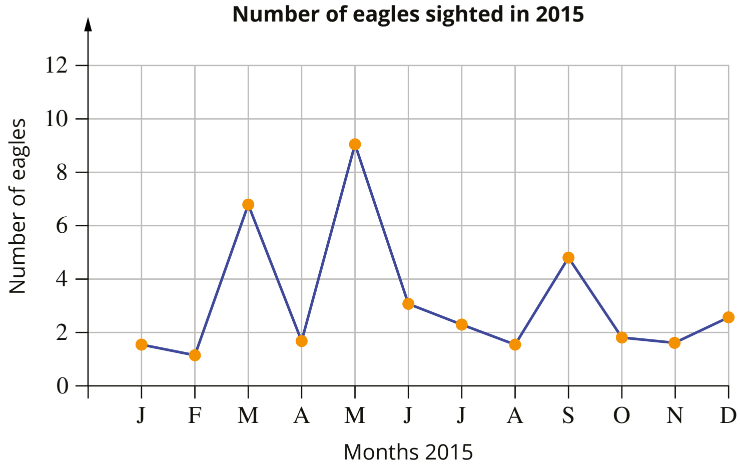


FIGURE 7.3.15 A line graph showing the number of eagle sightings in 2015, with lines ruled from each point to the next

SKILLBUILDER L N

Interpreting the slope of a linear graph

Scientists often represent a relationship between two variables as a graph. For directly proportional relationships, the variables are connected by a straight line, where the slope (or gradient) of the line represents the constant of proportionality between the two variables.

The slope or gradient of the line is defined as the ratio of change between two points in the vertical axis (ΔY), divided by the change between two points in the horizontal axis (ΔX) (Figure 7.3.16). In other words, it measures the rate at which one variable (the dependent variable) changes with respect to the other (the independent variable).

The graph below has two straight lines with different slopes. The steeper slope (blue line) indicates that the rate of change is higher. This means the change is happening more quickly. On the other hand, the flatter slope (purple line) indicates that the rate of change is lower. This means the change is happening more slowly.

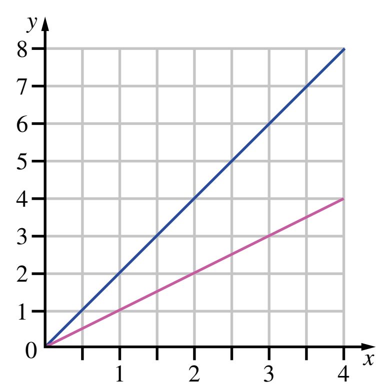


FIGURE 7.3.16 The slope of a line in a linear graph represents the ratio of change between two points.

FIGURE 7.3.17 The paralysis tick (*Ixodes holocyclys*)

Worked example 7.3.1

PLOTTING DATA: PARALYSIS TICK POPULATION CHANGES

The paralysis tick (*Ixodes holocyclys*) (Figure 7.3.17) is a parasite that feeds on animal blood (including human blood) and inhabits the eastern coastline of Australia. The paralysis tick injects toxins that can cause paralysis, tick-borne diseases and severe allergic reactions in humans and animals. The paralysis tick is found in a variety of habitats, but thrives in warm, humid environments such as wet sclerophyll forests and rainforests.

A survey of adult paralysis tick populations was undertaken in Wallingat National Park, northeast of Newcastle in New South Wales. The survey was conducted from December 2014 to May 2015 and the data obtained is presented in Table 7.3.1 and Figure 7.3.18.

TABLE 7.3.1 Population counts of adult paralysis ticks (*Ixodes holocyclys*) in Wallingat National Park, New South Wales between December 2014 and May 2015

Month	Dec	Jan	Feb	Mar	Apr	May
Number of adult ticks	1108	903	817	298	183	124

Create a line graph using the tick population data

Thinking	Working
Identify the independent variable	Month
Identify the dependent variable	Number of adult ticks
Label each axis (include units if required)	*x*-axis: number of adult ticks; *y*-axis: month
Identify the range of the data values	Population count: 124–1108
Determine an appropriate scale for the *y*-axis	0–1200
Identify appropriate labels for the *x*-axis	December, January, February, March, April, May
Add heading to the graph	Adult paralysis tick (*Ixodes holocyclys*) population counts in Wallingat National Park, NSW, December 2014 – May 2015
Plot the data points	Refer to Figure 7.3.18
Draw a line from one point to the next	Refer to Figure 7.3.18

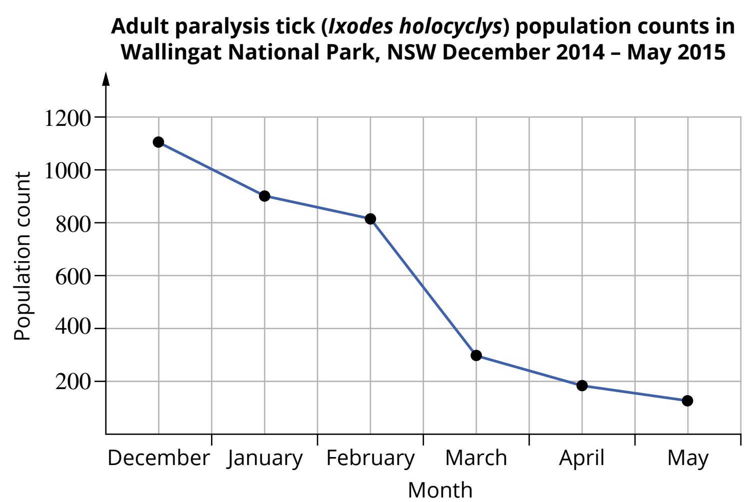


FIGURE 7.3.18 Population counts of adult paralysis ticks (*Ixodes holocyclys*) in Wallingat National Park, New South Wales between December 2014 and May 2015

Worked example: Try yourself 7.3.1

PLOTTING DATA: PARALYSIS TICK POPULATION CHANGES

The following year, another population survey of adult paralysis ticks was conducted in the same area. This time, population counts were conducted each month of the year. The data from this population survey are presented in Table 7.3.2.

TABLE 7.3.2 Population counts of adult paralysis ticks (*Ixodes holocyclys*) in Wallingat National Park, New South Wales between January and December 2016

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of adult ticks	987	874	203	121	106	93	84	368	630	780	950	1309

Create a line graph using the tick population data.

POPULATION EXPLOSIONS

Exponential growth is normal for some plants and animals when environmental conditions are favourable and resources are abundant. Because these conditions generally last only a short time, exponential growth is usually short-lived. But if favourable conditions continue, then a **population explosion** may occur.

Salvinia fern is a free-floating aquatic weed that often has population explosions (Figure 7.3.19). It can survive for up to 20 months in dry conditions. But under favourable environmental conditions, such as high nutrient levels, it can double its population every 2–5 days. If these conditions continue, *Salvinia* will form a dense mat on top of a waterway, preventing other aquatic plant life from receiving sunlight. Due to its growth rate and damage to aquatic habitats, this introduced species is declared as a prohibited weed throughout Australia.

FIGURE 7.3.19 Giant salvinia fern (*Salvinia molesta*) is one of the world's most troublesome aquatic weeds. This species can double its population size in 2–5 days under favourable conditions.

Population explosions can occur if populations grow exponentially over a long period of time.

Prickly pear population explosion

The expansion of the prickly pear (*Opuntia* species) is an example of a population explosion over a long period of time. The species invaded the Australian landscape during its introduction in 1788 and continued spreading until its control in the 1920s. The species is prone to exponential population growth, and the Australian environment provided favourable conditions for a population explosion.

Bioclimates found in Australia are similar to the prickly pear's natural habitat in the Americas. This provided suitable conditions for population growth and survival, with no species naturally limiting its growth. Reproduction and spread was well facilitated, with new plants quickly establishing from seeds or pads (pieces of plant tissue). The seeds can germinate years after they have been planted, and pads that break off the plant have such large water and nutrient stores that they can propagate after months of being separated from the original plant. Birds feed heavily on the prickly pear fruit, spreading seeds in their droppings. Early settlers also facilitated their population explosion, with plants and seeds distributed throughout Australia through:

- deliberate introduction of plants for the cochineal industry
- use as food for livestock during droughts (livestock manure provided a nutrient-rich environment for germination)
- use as decorative plants in home gardens.

Species that are likely to experience population explosions are those that have rapid rates of reproduction, are readily adaptable to new conditions, and have no limiting factors—such as predators—in their environment. Such species often successfully invade new environments.

The population explosion of prickly pears was so great that by 1920, more than 60 million acres of land had been infested, and the species was spreading at rates of over 1 million acres a year (Figure 7.3.20).

Early settlers depended on the land for agriculture. Desperate farmers tried everything to remove the prickly pear from their land, including poisoning, burning and crushing the plant. However, the expense of these methods bankrupted many farmers, who were already under pressure during wartime.

FIGURE 7.3.20 Australian land under the stranglehold of a prickly pear population

BIOFILE S

An explosion of algae

An algal bloom is a population explosion of aquatic phytoplankton (algae or cyanobacteria), causing water to change colour and become toxic (Figure 7.3.21). A common culprit in lakes and ponds is the cyanobacterium *Anabaena*.

FIGURE 7.3.21 The algal bloom outbreak on the surface of this pond is evident in the dense green colour of the water.

From 1880 to 1926, the Australian Government conducted research and provided monetary rewards to anyone who could assist in the control of the prickly pear. In 1926, the cactus moth (*Cactoblastis cactorum*) was introduced to Australia from South America. The moth larvae feed on the prickly pear flesh and destroy the plant. It took six years to control the prickly pear population explosion. However, the species still exists in Australia—mostly in cooler areas, where the bioclimate is less favourable for the survival of the cactus moth.

Cane toad population explosion

The cane toad (*Rhinella marina*) is a large amphibian native to South and Central America (Figure 7.3.22). They are robust, ground-dwelling predators that feed largely on insects. Cane toads have leathery, dry skin and can be grey, yellow, reddish–brown or olive–green in colour. Most adult cane toads reach 15 cm in length; however, the largest female measured was 24 cm and weighed a huge 1.3 kg.

FIGURE 7.3.22 The cane toad has a strong defence mechanism: highly poisonous toxins produced by glands in its skin.

The cane toad was introduced to Australia from Hawaii in 1935 as a **biological control** method for the control of the cane beetle that was destroying Queensland sugarcane crops. Unfortunately, the cane toad had little effect on the cane beetle populations, because the toads can't jump very high. The beetle simply stayed on the upper limbs of the sugarcane, out of reach of the toads. The cane toads soon spread through the local environment, breeding rapidly and exploding in numbers.

The cane toad has many features that have facilitated its population explosion.

- Rapid dispersal—The cane toad expanded its range through northern Australia, and is now found as far south as Port Macquarie in New South Wales. It is moving westward at a rate of 40–60 km per year.
- Rapid reproduction—Cane toads have a rapid rate of reproduction and breed all year round. They lay eggs in still or slow-moving water and produce more eggs than most amphibians. One female can lay 8000–30 000 eggs at one time, with the eggs hatching in just 2–3 days.
- Highly adaptable—Cane toads are adapted to a wide range of environments, which has helped facilitate its exponential growth in Australia. Cane toads are well suited to varied climates and habitat, being found in sand dunes, rainforest, mangroves, grassland and even urban areas. While insects are its staple diet, cane toads feed on many alternative food sources, including household scraps and pet food.
- Lack of predators—The cane toad has no current predators in Australia, or diseases to which it is susceptible. Its highly toxic skin secretions are often fatal to any organism that tries to eat it—even freshwater crocodiles.

Environmental impacts

Cane toads impose a range of environmental impacts.

- Cane toads have caused declines in native predators, such as kookaburras (Figure 7.3.23), northern quolls and goannas, which die after ingesting the toad. The cane toad also competes with native species for shelter, space and food resources.
- Cane toads pose a risk to human and domestic pet health, due to their highly poisonous skin secretions.
- Indigenous Australians using traditional food sources have also been affected, because native species numbers have declined.

FIGURE 7.3.23 Native species, such as the kookaburra, that feed on amphibians are often killed by the cane toad's poisonous skin secretions after ingesting the toad.

Population management and control

Local habitats can be protected by humanely disposing of the cane toads and their eggs. But due to the population explosion of the cane toad and its ability to adapt to its surroundings, a broadscale method of control is unlikely to be effective. Conservationists are currently putting their efforts into protecting the native species affected by the cane toad. This appears promising. Some species, such as the red-bellied black snake, have already demonstrated rapid evolutionary adaptations in response to the introduction of the cane toad.

Population explosions of the cane toad are expected to continue, with researchers finding that the species has developed the ability to reproduce earlier in its life cycle. Toads on the 'invasion front' (those colonising new environments) have faster growth rates and reach breeding size earlier than other cane toad populations. This is helping to drive the cane toad population explosion and increase its distribution across the Australian landscape (Figures 7.3.24 and 7.3.25). You will learn more about the evolution of cane toads in Chapter 10.

GO TO ➤ Section 10.2 page 467

FIGURE 7.3.24 Cane toad populations continue to grow exponentially in Australia, with the 'invasion front' moving south and westward at alarming rates.

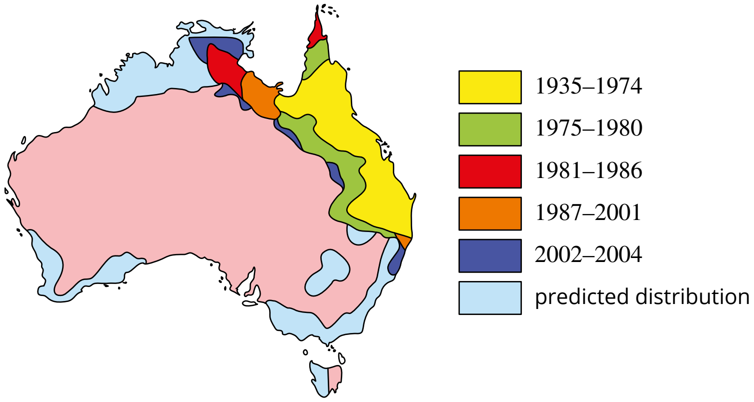


FIGURE 7.3.25 The cane toad's distribution across Australia has expanded since its introduction and is expected to continue as it adapts to conditions further south and global temperatures increase.

PA 3.1

WS 3.2

7.3 Review

SUMMARY

- Population size, growth and density is affected by four processes:
  - births (natality)
  - deaths (mortality)
  - immigration (individuals entering a population)
  - emigration (individuals leaving a population).
- Geographic distribution or range is all the places where a particular species can be found.
- The density of a population is the number of individuals per unit of area or volume.
- Exponential growth is the rapid increase in the size of a population, shown as a J-shaped curve on a graph.
- Continued exponential growth can result in a population explosion (a rapid rate of population increase).
- Population explosions can occur if there are no factors limiting population growth.
- The prickly pear and cane toad are examples of species that have successfully invaded and expanded their range across Australia. Their success in their new environment is due to their adaptability, high reproductive rates and lack of limiting factors, such as predators.

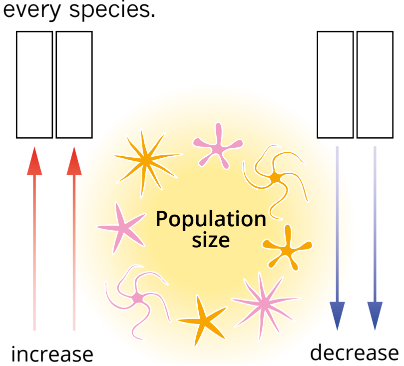
KEY QUESTIONS

1 Compare the concepts of distribution and abundance of a species.

2 Describe the introduction of the prickly pear to Australia.

3 What is biomass? When might we use this?

4 Label the blanks in this diagram with the four processes that affect the population size of every species.



5 **a** Describe an exponential growth pattern.
b In what kinds of organisms and under what conditions could this kind of population growth occur?
c Describe what happens if favourable environmental conditions allow exponential growth to continue.
d Provide an example of this.

Chapter review

07

KEY TERMS

abiotic
abundance
altitude
artificial selection
aspect
atmosphere
biodiversity
biogeochemical cycle
biological control
biomass
biome
biosphere
biotic
carrying capacity
community
conservation
diversity
dormancy
ecosystem
emigration
exponential growth
geographic distribution
habitat
hydrosphere
immigration
individual
invasive species
keystone species
lithosphere
microhabitat
migration
mortality
natality
natural selection
population
population density
population explosion
predator
prey
selection pressure
shelter
species
terrestrial
tolerance range
topography

REVIEW QUESTIONS

1 What is a selection pressure? Provide an example of a biotic and an abiotic selection pressure.

2 A blue-tongued lizard lives in an open, woodland habitat where it can bask in sunlight on rocks and easily find small insects to eat. When flooding occurs, the lizard must find shelter on higher ground. The habitat is subject to strong winds that can blow small birds and hatchlings from their nests.

- **a** Which abiotic factors are an advantage to the blue-tongued lizard?
- **b** Which factors disadvantage it?
- **c** Which factors have a neutral effect?

3 Read the following information on the Weddell seal (*Leptonychotes weddellii*) and list all the abiotic factors present in the environment.

'The Weddell Seal lives in the cold climate of Antarctica, spending most of its time on the coastline ice (also called fast ice) where it rests in the sunlight, moults and breeds. It feeds underwater, having the ability to travel under sea ice, breathing through cracks in the ice when needed.'

4 Below is a list of factors that influence ecosystems. State whether each one is a biotic or abiotic factor.

- **a** water
- **b** algae
- **c** pH
- **d** soil
- **e** trees
- **f** beetles
- **g** salinity
- **h** hawk

5 Explain how selection pressures in the environment drive the evolution of a species. Give an example.

6 What is tolerance? Give an example of an organism that tolerates a specific environment's abiotic factors.

7
- **a** What is the biosphere, and why can it be regarded as an ecosystem?
- **b** The birds in a backyard aviary include galahs, corellas and sulphur-crested cockatoos. Is the aviary an ecosystem? Explain your answer.

8 Outline one example of biological control of an invasive species.

9 A keystone species is critical to the stability of a whole ecosystem. Give one example of a species like this and explain what makes it a keystone species.

10 Name and describe the three types of population distribution.

11 What type of measurement would you use to describe the density of species in each of these situations? Explain your answer in each case.

- **a** sheep in a paddock
- **b** grass in a field
- **c** leaves on a plant

12 What is exponential population growth?

13 Scientists often use line graphs to represent changes in populations over time. On a graph with two sloped lines, what does the steeper sloped line indicate?

- **A** a faster rate of change
- **B** a slower rate of change
- **C** the same rate of change
- **D** a much slower rate of change

14 The rate of change of a straight line on a graph is given by the:
- **A** *y*-intercept
- **B** *x*-intercept
- **C** gradient
- **D** area under the graph

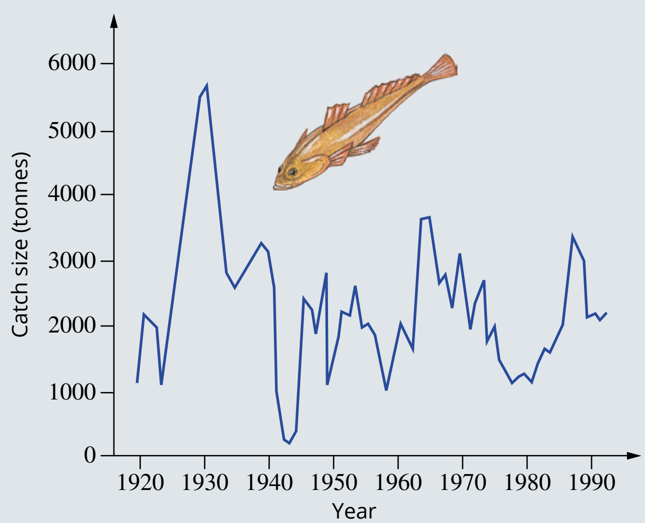
15 A noxious weed is introduced into an environment and exhibits exponential population growth. Environmental conditions are favourable, so the population continues to grow exponentially. What is said to be occurring?

16 Select a species that has become invasive after being introduced to Australia, and explain the factors that have facilitated the species' exponential population growth.

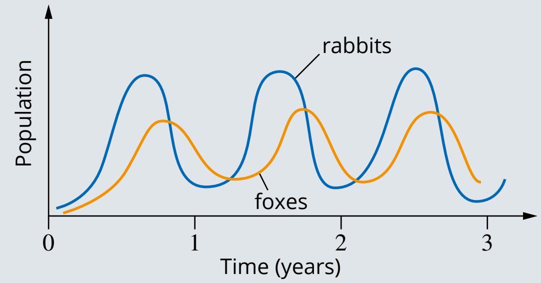
17 Which of the following situations describes a population that is increasing in size? (B = birth, D = death, I = immigration, E = emigration)
- **A** (B + D) > (I + E)
- **B** (B + E) > (D + I)
- **C** (D + E) < (B + I)
- **D** (B + E) < (D + I)

18 Describe two ways in which humans facilitated the prickly pear population explosions in Australia.

19 Consider the following graph, which shows the annual catch of tiger flathead from 1920 to 1992. During which period was the tiger flathead population most stable? Explain your answer.



20 Consider the following graph, which shows changes in the rabbit and fox populations on an isolated area of open farmland in western Victoria.



- **a** What factors might have caused the initial growth in the rabbit population?
- **b** Why does the growth in fox numbers follow that of rabbits?
- **c** What factors could cause the decline in the rabbit population?
- **d** How is it that rabbit numbers are able to build up again in the following year?
- **e** What would happen to the fox population if the rabbit population suddenly crashed from the effects of calicivirus? Show this by extending the graph.

21 After completing the Biology Inquiry on page 310, reflect on the inquiry question: How do environmental pressures promote a change in species diversity and abundance? Using at least five key terms from this chapter, discuss how selection pressures result in population change over time.

CHAPTER 08

Adaptations

This chapter examines how adaptations increase an organism's ability to survive. You will learn about the different types of adaptations in plants and animals, and how these adaptations enable organisms to survive in a broad range of environments. You will also learn about the adaptations that Charles Darwin noticed in the finches of the Galápagos Islands and Australian flora and fauna, and how these observations led to the development of the theory of evolution by natural selection.

Content

INQUIRY QUESTION

How do adaptations increase the organism's ability to survive?

By the end of this chapter you will be able to:

- conduct practical investigations, individually or in teams, or use secondary sources to examine the adaptations of organisms that increase their ability to survive in their environment, including: CCT ICT WE
  - structural adaptations
  - physiological adaptations
  - behavioural adaptations
- investigate, through secondary sources, the observations and collection of data that were obtained by Charles Darwin to support the theory of evolution by natural selection, for example: ICT L
  - finches of the Galápagos Islands
  - Australian flora and fauna

8.1 Structural adaptations

BIOLOGY INQUIRY CCT ICT WE

Adaptations for flight

How do adaptations increase the organism's ability to survive?

COLLECT THIS...

- 3–4 A4 sheets of paper per student
- marker tape or paper
- tape measure
- tablet or computer to access the internet

DO THIS...

1. Working in groups of three or four, access the internet to find short videos of the following birds in flight:
   a albatross **b** hummingbird **c** owl.
2. Research the wing structures of these birds and draw rough diagrams of each wing. Note the differences.
3. Based on your research, come up with a paper plane design for your group. For this activity, flight distance is important.
4. Each member of the group is to make a paper plane (bird) of your group's design. Write your initials and the group's name on the plane.
5. Mark a line at the front of the room. This represents food and nesting sites.
6. Stand approximately 3.5 m from the line and throw your bird.
   - Each bird that crosses the line survives and breeds. Keep these.
   - Each bird that doesn't cross the line dies. Put these in the recycling bin.
7. Record the number of birds from each group that survived.
8. Students with a dead bird make a new plane (a hatchling) to match one of the designs that survived.
9. Repeat steps 6–8 three times.
10. Now look at what designs have survived. This is a simulation of natural selection against an environmental challenge.
11. As a class, discuss how the different wing structures are appropriate for the lifestyle and diet of each bird, and how the natural selection you have just investigated would affect the evolutionary process.

RECORD THIS...

Describe how the numbers of each type of plane changed by generation.

Present a hypothesis to test the inquiry question, 'How do flight adaptations increase a bird's ability to survive?'

REFLECT ON THIS...

What features of wings are adaptations to the environments and diets of different bird species?

How do selection pressures in the environment result in adaptation?

How do adaptations increase the organism's ability to survive?

Organisms have different features that enable them to survive and reproduce in different environments. These features have evolved in response to various environmental factors, and are known as **adaptations**. Adaptations enable animals and plants to live in extreme environments, access resources and mates, defend themselves and their territory, and communicate and interact with their own and other species. Adaptations are the result of the evolutionary process of **natural**

selection, in which those organisms that are best suited to their environment survive and reproduce, passing on their advantageous adaptations to their offspring.

Structural adaptations are anatomical or morphological features that improve an organism's ability to cope with abiotic and biotic factors in their environment, increasing their chances of survival and reproduction. These are physical characteristics relating to body size and shape.

STRUCTURAL ADAPTATIONS OF PLANTS

Water is essential for photosynthesis. Therefore, many of the structures found in plants are adaptations to reduce water loss caused by salinity, heat and wind in their environment. Some of these adaptations include:

- reduced leaf surface area
- fewer stomata
- stomatal hairs that create a humid microclimate
- sunken or protected stomata
- thick, waxy cuticle
- extensive root systems
- rolled leaves
- leaves orientated away from sunlight
- leaf **abscission** (shedding).

Some adaptations to hot, dry environments are very similar to adaptations to cold environments. This is because in very cold climates, water freezes and becomes inaccessible to the plant. For this reason, cold climates are also often dry environments. When the air is cold and dry, plants lose water through transpiration, just as they do in hot, dry environments. Plants that grow in hot, dry environments are known as **xerophytes** (from Greek 'xeros', meaning 'dry', and 'phyton', meaning 'plant structure').

Stomata (singular stoma) are pores in the surface of a leaf. These pores are an adaptation of land plants to regulate gas exchange and water loss (transpiration) with the environment.

Structural adaptations to hot, dry environments

Cacti are well-known examples of xerophytes. Xerophytes have adaptations that conserve moisture and prevent the leaf temperature from rising too much. They also have an increased tolerance for desiccation (drying). Some of the adaptations of xerophytes are shown in Figures 8.1.1 and 8.1.2.

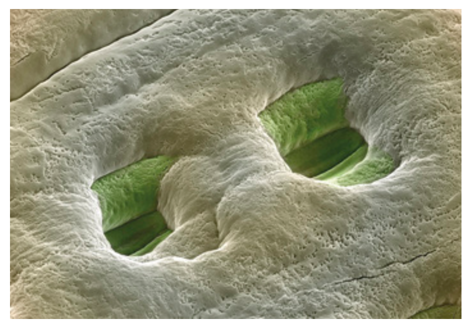


FIGURE 8.1.1 Scanning electron microscope image of the sunken stomata of a needle leaf of the coastal Sitka spruce (*Picea sitchensis*)

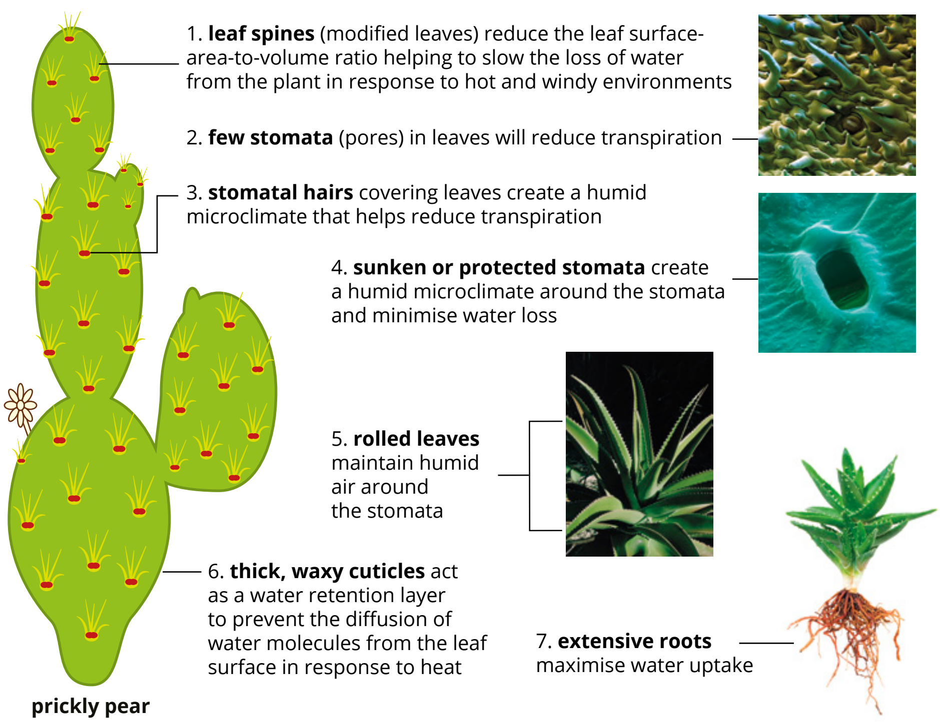


FIGURE 8.1.2 Plants that live in harsh, dry environments (such as deserts) have evolved adaptations that enable them to conserve water.

Rolled leaves

Marram grasses (*Ammophila* species) are xerophytes that grow well in the salty, sandy soils of coastlines (Figure 8.1.3a). The leaves of marram grasses are lined with bubble-shaped (bulliform) cells. When conditions are hot and dry, the bulliform cells partially collapse. This causes the leaves to roll inwards so that the two sides of the blade almost touch. Hairs on the inside of the rolled-up leaf trap moisture, creating a humid microclimate (Figure 8.1.3b). The humidity reduces the concentration gradient between the outside and inside of the leaf, which in turn reduces transpiration. Because of this and other adaptations, these grasses have been used to stabilise sand dunes that are prone to erosion.

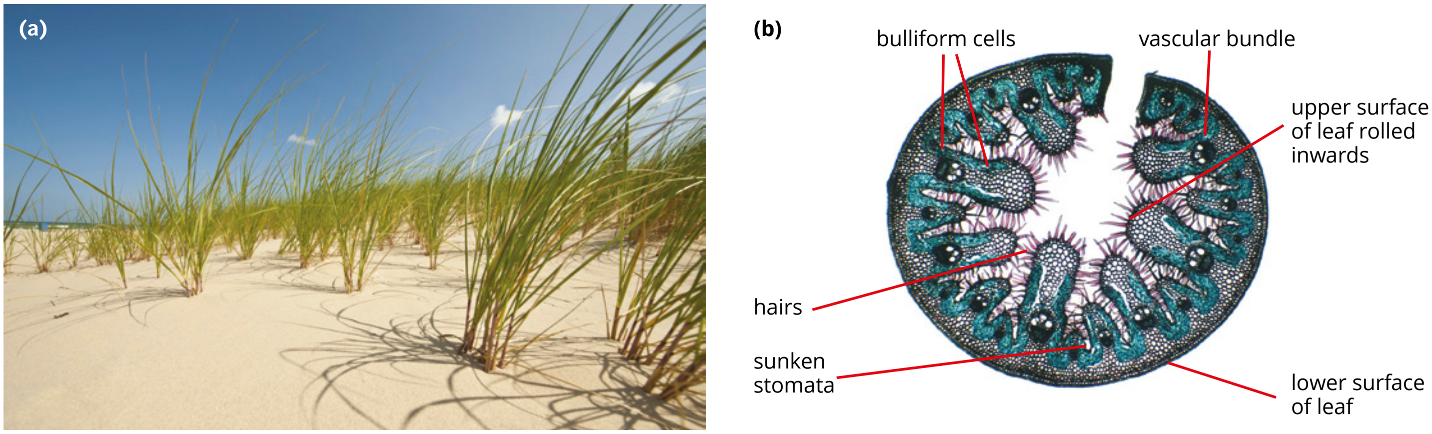


FIGURE 8.1.3 (a) Marram grasses (*Ammophila* species) grow well in the salty, sandy soils of coastlines. They have adaptations that allow them to survive in this dry, salty environment. (b) One of these adaptations is leaf rolling, which enables the plant to trap moisture and reduce water loss. A cross-section of a rolled leaf is shown here.

Leaf orientation

Eucalypt trees have structural features that enable them to survive in hot, dry environments. They have hard leaves with waxy cuticles on both sides to reduce water loss. In many species, the leaves also hang vertically, which reduces the amount of direct sunlight they receive (Figure 8.1.4). This reduces transpiration and water loss.

FIGURE 8.1.4 *Eucalyptus* leaves are well adapted to hot, dry environments.

BIOFILE CCT

Lithops

Lithops is a genus of succulent plants that live in dry, rocky environments in southern Africa. They are called stone plants or pebble plants because of their stone-like appearance (Figure 8.1.5). This appearance helps them to blend in with their surroundings, so they are less likely to be eaten by herbivores.

FIGURE 8.1.5 *Lithops* or stone plants have unique structures to cope with their hot, dry environment.

Another unusual feature of *Lithops* is that most of the leaves grow underground. While this adaptation helps to reduce water loss, it also makes it difficult for the leaves to access vital sunlight. To overcome this problem, the plant has evolved translucent tissue on its leaf tips. This tissue allows sunlight to be magnified through to the chloroplasts, which are deep within their underground leaves.

Lithops can also tolerate a diverse temperature range, from a minimum temperature of –16.4°C to a maximum of 68.7°C. The plant's enzymes have a broad functional temperature range to enable the plants to survive in these extreme environments.

Structural adaptations to cold, dry environments

Plants in cold environments can protect themselves from water loss through transpiration by reducing the surface area of the leaf. Conifers such as pines (*Pinus* species) achieve this by growing their leaves as needles (Figure 8.1.6a). Some cold-adapted plants shed their leaves entirely during winter, a process known as leaf abscission. Trees that do this are called **deciduous** (Figure 8.1.6b). Alternatively, the leaves of cold-adapted plants may have a waxy cuticle to prevent water loss, just like heat-adapted plants.

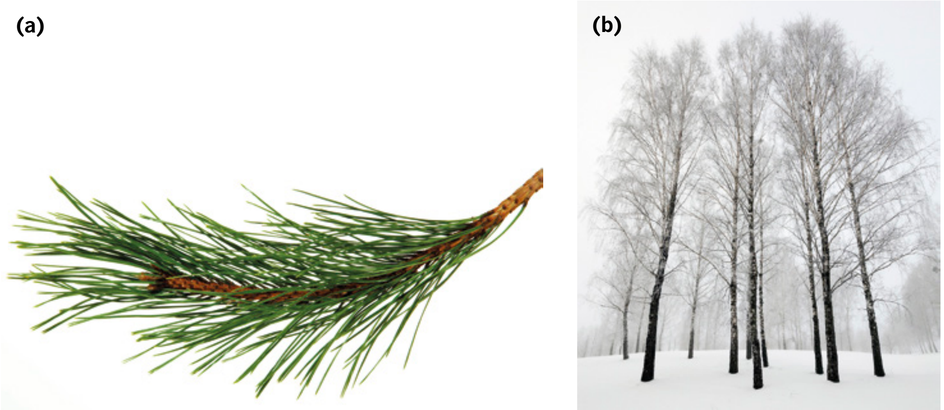


FIGURE 8.1.6 (a) In cold, dry environments, conifers such as pine trees (*Pinus* species) grow their leaves as needles. This reduces the surface area through which water can be lost. (b) A more extreme adaptation to cold, dry environments is leaf shedding. Deciduous trees shed their leaves altogether in winter, pausing photosynthesis and growth, but conserving water.

BIOLOGY IN ACTION S

Greenhouses

Some plants are so highly specialised for their environment that growing them outside of that environment requires special care. In particular, making food plants available out of season takes a great deal of work and energy. One of the most common techniques for this sort of agriculture is the humble greenhouse.

Modern greenhouses work by trapping solar radiation, leading to a warmer environment inside the greenhouse. Humidity levels are maintained by providing water—which, given the enclosed warm environment, remains moist—and adequate ventilation is necessary to prevent the plants from suffocating. In cold environments, keeping a greenhouse warm and well-ventilated can be very expensive in terms of energy. This means that producing fruits and vegetables out of season is a costly process.

The concept of manipulating the local environment to produce vegetables out of season dates back to the year 30, when Tiberius, Emperor of Rome, demanded out-of-season cucumbers. But the earliest report of an active greenhouse in which the temperature could be manipulated directly comes from 1599 in Holland, where the French botanist Jules Charles designed a structure to house tropical plants. These plants, adapted to their native hot and humid environment, would not survive the much colder, drier conditions in Holland.

These days, agricultural greenhouses are far larger and more complex than Charles' original design (Figure 8.1.7), but the basic principle remains the same.

FIGURE 8.1.7 Large-scale industrial greenhouses are used to grow plants out of season, to speed up growth and ripening and to grow plants outside their native environment.

FIGURE 8.1.8 Plants in tropical rainforests are adapted to cope with the excess water in their environment. Large, thick, waxy leaves with pointed tips encourage water to run off, preventing fungal growth in warm wet environments.

FIGURE 8.1.9 The Arabian sand cat (*Felis margarita*) is a true desert animal. It is one of the smallest members of the cat family and can heat up and cool down very quickly compared with larger cat species. This is advantageous in its desert environment.

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Structural adaptations to warm, wet environments

Not all plant adaptations are related to conserving water. Some structures are adaptations to help plants survive in environments with excess water. Plants that live in tropical rainforests have to cope with high rainfall and high humidity. Some structural adaptations of plants in tropical rainforests are:

- thin bark—plants in tropical rainforests do not need thick bark to prevent water loss
- thick, waxy leaves (Figure 8.1.8)—water runs off these leaves quickly to prevent fungal growth in warm, wet environments
- a 'drip tip' on leaves (Figure 8.1.8)—a pointed end that funnels water off the leaves and prevents fungal growth
- buttressing, stilt roots and prop roots
  - buttresses are the large ridges at the base of some rainforest trees, while stilt and prop roots are rapidly growing above-ground root systems
  - buttress and above-ground roots allow large trees to maintain stability in shallow soils
- epiphytes ('epi', meaning 'on' and 'phytes', meaning 'plant')—plants that grow on other plants, such as ivy and creepers
  - epiphytes can grow in rainforest environments because they climb above the shady undergrowth that would otherwise prevent them getting enough light to grow.

STRUCTURAL ADAPTATIONS OF ANIMALS

All animals have evolved structures that enable them to survive in their environment. These adaptations allow animals to cope with abiotic factors, such as temperature and water availability, and biotic factors, such as predators, prey and competitors.

Some examples of the structural adaptations of animals include:

- thick fur and blubber (fat) to insulate against cold
- bright feathers to help attract mates
- large ears to increase heat loss
- small ears to reduce heat loss
- webbed feet and flippers for swimming
- spines for protection against predators
- overall body shape and size (surface-area-to-volume ratio) to conserve body heat or water
- patterned body coverings for camouflage.

Surface-area-to-volume ratio and structural adaptations

If two objects have the same shape but are different sizes, the smaller object will have a larger surface area relative to its volume. You learnt in Chapter 3 how the relationship between surface area and volume applies to cells. This relationship also applies to larger structures and whole organisms.

A larger surface-area-to-volume ratio means that a small animal can cool down and heat up much more quickly; this strategy is well suited to hot, dry climates. A large animal of roughly the same shape will have a greater volume relative to its surface area, meaning that it can more effectively conserve body heat. This strategy is well suited to cold, icy environments.

Cat species are an excellent example of this: compare a tiny desert sand cat (*Felis margarita*) (2–4 kg) (Figure 8.1.9) with an alpine snow leopard (*Panthera uncia*) (35–55 kg) (Figure 8.1.10). The sand cat's small size allows it to lose and gain heat quickly in its hot, dry environment, while the snow leopard's large size allows it to conserve heat in its cold environment.

There are variations to this rule—for example, lions are large cats that are found in hot, dry environments. But lions, unlike sand cats, experience advantages due to their larger size, such as the ability to capture larger prey. These benefits outweigh the advantage of being small, so lions must also use behavioural strategies to cool their larger bodies.

The relationship between surface area and volume can also be seen in animals that are the same size but of different shapes. This example is best illustrated by comparing the desert bird, the Kori bustard (*Ardeotis kori*) (Figure 8.1.11) with the emperor penguin (*Aptenodytes forsteri*) (Figure 8.1.12).

Both birds are roughly the same size: the Kori bustard grows up to 18 kg, while the emperor penguin ranges from 22 kg after the breeding season to 45 kg before breeding. But the Kori bustard has long legs and a long neck, while the emperor penguin has extremely short legs and a short neck. The Kori bustard's long legs and neck give this bird a larger surface area relative to its volume than the emperor penguin. Just like the two different-sized cat species, this means that the Kori bustard will be better able to regulate temperature in the variable environments of its native southern Africa, while the emperor penguin will be better able to conserve body heat in the Antarctic.

FIGURE 8.1.10 Snow leopards (*Panthera uncia*) are larger cats found in snowy, alpine environments. Their large size coupled with their thick coat allows them to conserve heat more effectively than smaller cats.

FIGURE 8.1.11 The Kori bustard (*Ardeotis kori*) may weigh up to 18 kg and is found in the deserts, savannahs and central plateaus of southern Africa. Male Kori bustards are one of the largest living animals capable of flight.

Larger animals are usually found in cold environments, because they have a lower surface-area-to-volume ratio and radiate less body heat per unit mass than smaller animals. A low surface-area-to-volume ratio allows large animals to conserve heat in cold environments.

Body coverings

The emperor penguin has many structural adaptations to cope with life in the harsh Antarctic climate. Penguins have four layers of thick, scale-like feathers, creating a windproof coat (Figure 8.1.12). They also have thick blubber to keep them warm while swimming in the icy ocean. Juvenile penguins have soft down for insulation, which is a more effective insulator on land than the adult feathers, but of little use in the sea. Juvenile penguins must moult before they can swim.

FIGURE 8.1.12 The emperor penguin (*Aptenodytes forsteri*) has mastered living in extremely cold environments. Its thick layer of feathers and blubber are two of many important adaptations that make this lifestyle possible.

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The term vascular refers to blood vessels. Highly vascularised tissues contain many blood vessels.

Vascular body parts

Animals in hot, dry climates may have large ears, long tails or a long body. These extremities are often highly **vascular**, which means they contain many blood vessels. This enables the animals to release body heat to the external environment, keeping their bodies cool. The fennec fox (*Vulpes zerda*) of the Negev Desert is an example of a desert dweller with highly vascularised ears (see Figure 8.1.13).

The cardiovascular system plays an important role in regulating the body temperature of animals. When the body is overheated, blood vessels expand, allowing blood to flow closer to the surface (i.e. the skin) and cool. When the body is cold, blood vessels constrict, and the blood flows away from the surface area to conserve heat. This method of **thermoregulation** is discussed further in Section 8.2.

FIGURE 8.1.13 The fennec fox (*Vulpes zerda*) has highly vascularised ears, which allow the fox to release heat rapidly, lowering its body temperature in the extreme desert heat.

Tearers and crushers: dental adaptations

Not all structural adaptations are related to temperature. Many structures are adaptations to meet dietary requirements: the arrangement and structure of teeth (**dentition**) is one of the most obvious of these. Compare the skull of the koala (*Phascolarctos cinereus*, Figure 8.1.14a) and the Tasmanian devil (*Sarcophilus harrisii*, Figure 8.1.14b).

The koala is adapted to eat the leaves of eucalypts. Eucalypt leaves are tough because of their high cellulose content, which makes them difficult for mammals to digest. The koala must chew the leaf thoroughly, mechanically breaking down as much of the leaf's fibre as possible before eating it. This is why koalas' molars are flat and wide (Figure 8.1.14a). When the jaw is closed, the molars sit directly on top of one another, making ideal structures for grinding and crushing leaves.

In contrast, the Tasmanian devil is a carnivore (Figure 8.1.14b). The molars are sharper and arranged so that one set sits inside the other when the jaw is closed, creating a shearing, scissor-like effect for tearing meat. You can often draw conclusions about the diet of an animal by examining its teeth and jaws.

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The structure of an animal's teeth is an adaptation to their diet.

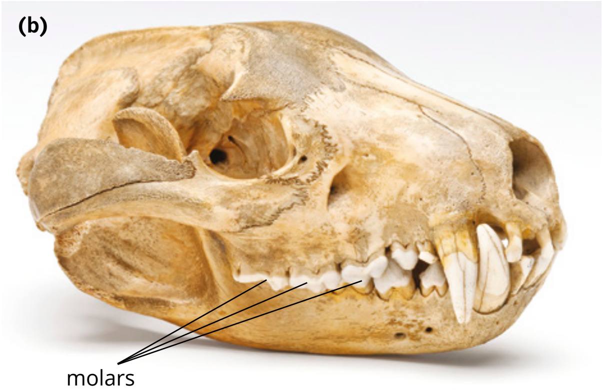

FIGURE 8.1.14 (a) The skull of the koala (*Phascolarctos cinereus*) clearly shows the flattened molars, adapted to mechanically grind tough eucalyptus leaves. (b) The skull of the Tasmanian devil (*Sarcophilus harrisii*) has sharp, biscuspid (two-cusped) molars that produce a scissor action for tearing meat.

BIOLOGY IN ACTION CCT ICT

Biomimicry

Biomimicry (also called biomimetics) involves people mimicking or copying structures or systems found in nature to develop new materials or products. Biomimicry is divided into three main areas: form, process and systems. Form biomimicry is the imitation of shape or structure. Process and systems biomimicry are covered on pages 358 and 365.

Form biomimicry is not a new discipline. For example, in the 1920s, aircraft designers copied the shape of a gull's wing in an attempt to build a more stable glider. The following are modern examples of biomimicry.

Form biomimicry: Bullet train design inspired by birds

When the Shinkansen bullet train travelled through a tunnel at high speed (up to 300 km/hr), air pressure changes caused a deafening sonic boom when it left the tunnel. Eiji Nakatsu, an engineer and keen birdwatcher, knew that kingfishers could perform a perfect splashless dive into water to catch fish. He used this knowledge to improve the design of the bullet train. A round beak would send shock waves in all directions (like the train as it left the tunnel). But the kingfisher's long, streamlined beak allows the water to flow past the beak, rather than being pushed in front of it. This greatly reduces the impact when it hits the water (Figure 8.1.15a, b).

Another source of noise from the bullet train was the pantograph, which is the structure on top of the train that receives electricity from overhead wires. Engineers tackled the problem using inspiration from the feathers of owls, which have almost silent flight. The engineers adapted a similar design, consisting of many small vortices, thus reducing the sound on the main part of the pantograph.

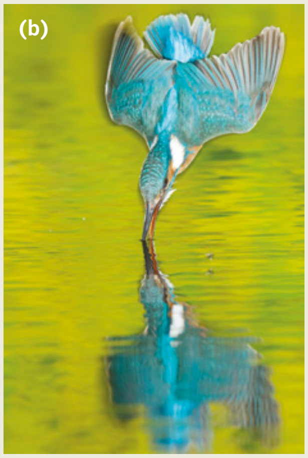

FIGURE 8.1.15 A kingfisher's long, streamlined beak (a) allows it to dive for fish without creating a splash (b). The Shinkansen bullet train's nose shape (c) is modelled on the kingfisher's beak. The streamlined shape solved the problem of sonic booms that occurred when the train travelled through tunnels at high speed.

These biomimicry design solutions allow the train to travel more quietly. The beak-like nose of the train also has the additional benefits of increasing speed by 10% and reducing electricity use by 15% (Figure 8.1.15c).

8.1 Review

SUMMARY

- An adaptation is an inherited characteristic that increases the likelihood of survival and reproduction of an individual organism in a particular environment.
- There are three main types of adaptation: structural, physiological and behavioural.
- Structural adaptations are anatomical or morphological body parts that help an organism to survive in its environment.
- Examples of structural adaptations of plants are:
  - reduced leaf surface area
  - fewer stomata
  - stomatal hairs to create a humid microclimate
  - sunken or protected stomata
  - thick, waxy cuticle
  - extensive root systems
  - leaf shape: rolled leaves; reduced surface area
  - leaves orientated away from sunlight
  - leaf abscission (shedding).
- Examples of structural adaptations of animals include:
  - thick fur and blubber (fat), which insulates against cold
  - bright feathers or skin to help attract mates
  - large surface-area-to-volume ratio of small animals to allow rapid heat loss in hot environments
  - small surface-area-to-volume ratio of large animals to conserve body heat in cold environments
  - large ears to increase heat loss
  - small ears to reduce heat loss
  - webbed feet and flippers for swimming
  - spines for protection against predators
  - patterned body coverings for camouflage.

KEY QUESTIONS

1. Describe a structural adaptation, listing two examples each for animals and plants. Explain how these structures enable animals and plants to survive in their environment.
2. Explain why the structural adaptations of plants to both hot, dry environments and cold environments are often quite similar.
3. Draw a diagram showing three different types of leaves that are adapted to different environments. Label the important structures. What sort of environments would you find these plants in?
4. What is meant by the term ‘vascularisation’? What is the adaptive benefit of highly vascular tissues in an animal?
5. Consider the structural adaptations of the animals and plants covered in this section that allow these organisms to survive in their environment. Choose an animal or plant and predict what would happen if you took this organism out of its environment and placed it in an environment at the opposite extreme (e.g. placing a heat-tolerant plant in a cold environment). Describe what you think would happen to that organism, and draw a diagram labelling the structural adaptations that are advantageous or disadvantageous in the different environments.
6. How does the ratio of surface area to body volume affect the ability of an animal to regulate its body temperature? Provide examples for a hot and cool environment.
7. Given your answer to Question 6, consider exceptions to the rule. For example, some large animals live in hot environments (e.g. lions, elephants). Their size is not advantageous in terms of heat regulation, but they have still evolved to be large. Explain why you think this might be the case.
8. Compare the dentition of a horse with the dentition of a dog (you should be able to find diagrams online or in a library). How do they differ? How are the teeth of each animal suited to their diet?

8.2 Physiological adaptations

Physiological adaptations affect functioning at different levels of organisation. They can range from the biochemical reactions that take place in organelles and cells to the physiological functions at the tissue, organ, system, or even whole organism level.

PHYSIOLOGICAL ADAPTATIONS IN PLANTS

Plants live in an incredible range of environments, from hot deserts and high mountain peaks to fast-flowing rivers and coastal zones. They need an equally impressive range of adaptations to cope in what are often stressful conditions. Physiological adaptations play an important role in enabling plants to cope with environmental challenges.

Crassulacean acid metabolism (CAM)

Crassulacean acid metabolism, also known as CAM photosynthesis, is an example of a physiological adaptation that reduces water loss in plants. It is most commonly found in plants living in dry environments, such as succulent plants in deserts. Some xerophytes and some plants adapted to saline conditions can minimise water loss during the heat of the day by using the CAM pathway.

In CAM plants, the stomata open only at night to collect carbon dioxide. Rather than using the carbon dioxide immediately, as non-CAM photosynthesising plants do, the plant stores the carbon dioxide in cell vacuoles as an organic compound called **malic acid**.

During the day, the malic acid is transported to the chloroplasts, where it is used to produce the carbon dioxide needed for photosynthesis (Figure 8.2.1). By storing the carbon dioxide required for photosynthesis at night, the plant can close its stomata during the heat of the day to reduce water loss. This physiological adaptation allows plants to survive in environments of extreme heat and aridity (dryness).

> The range of environmental conditions in which an organism can survive is called its **tolerance range.**

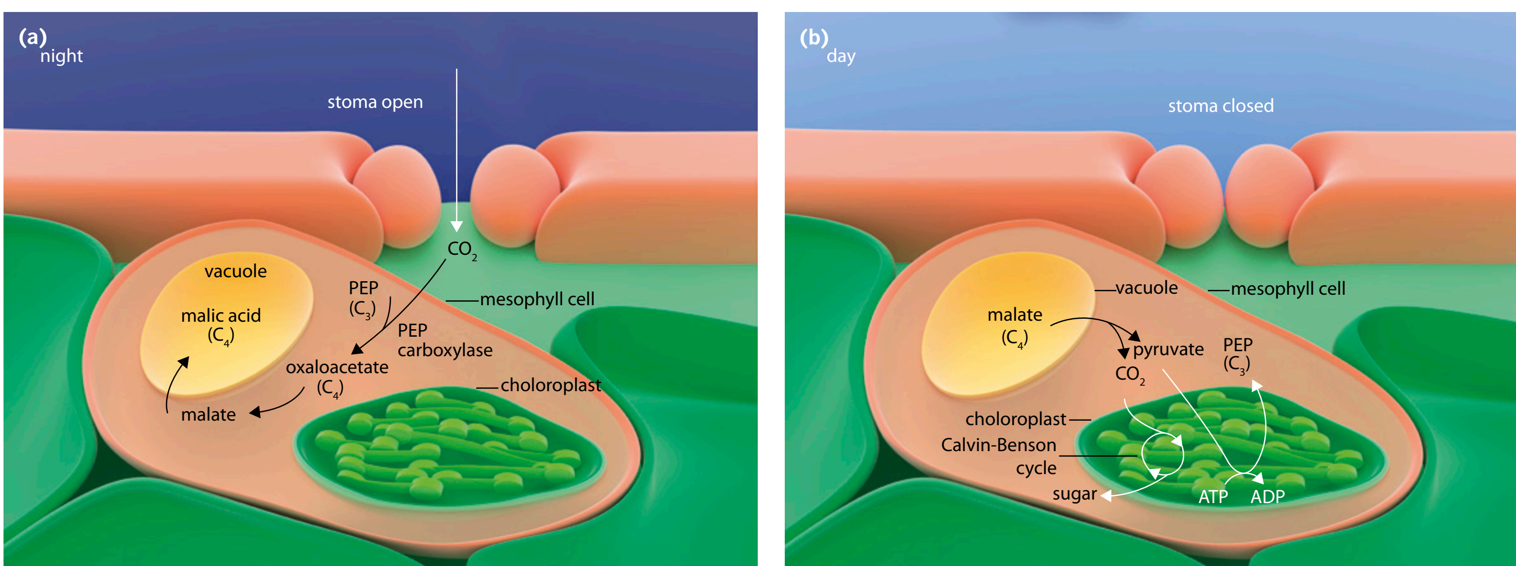

FIGURE 8.2.1 A summary of the complex CAM metabolic pathway of some plants in hot and dry or saline environments. (a) During the night, the stomata open and allow the plant to absorb carbon dioxide, which is converted to malic acid. (b) During the day, the stomata are closed to avoid losing precious water. The stored malic acid is converted to malate before being transported to the chloroplast as carbon dioxide, where the energy-producing final steps of photosynthesis can now take place.

Frost tolerance

FIGURE 8.2.2 Physiological adaptations—such as increasing solute concentrations, producing frost-inhibiting proteins and changing cell membrane composition—allow some plants to survive in extremely cold climates.

Extreme cold can be very damaging—even lethal—to plants that are not adapted to cope with such conditions. Ice crystal formation inside cells bursts the cell membranes, killing the cells. Cold temperatures can also decrease enzyme activity and change the fluidity of cell membranes, both of which affect a wide range of physiological processes in the plant. To overcome these problems, plants living in cold climates have evolved strategies that enable them to tolerate freezing temperatures (Figure 8.2.2).

A high concentration of solutes, such as sugars and salts, lowers the freezing point of water. Plants that can accumulate high concentrations of these solutes in their leaves are therefore less likely to be damaged by freezing temperatures.

Some plants produce proteins that reduce the risk of cell damage from freezing. **Antifreeze proteins** inhibit the growth and recrystallisation of ice crystals by binding to them. **Dehydrin** proteins bind to water molecules inside the cell, changing the structure of the water and stabilising the cell membrane.

Plants can also change the lipid composition of their cell membranes to improve function in cold temperatures.

Enzymes catalyse metabolic reactions only within certain temperature ranges. They denature (break down) at high temperatures and are inactive at low temperatures.

Regulation of salinity

High **salinity** (salt content) is a major problem for many agricultural crops. In many areas, over-irrigation of agricultural land has resulted in highly saline soils, which most food crops cannot tolerate. Saline soils disrupt water and nutrient uptake by the roots by altering the concentration gradient, ultimately suppressing plant growth and starving the plant. When salt enters the plant's cells, it causes ion imbalance, inhibits metabolic processes and eventually leads to cell death.

Plants living in saline environments, such as coastal dunes, salt marshes or salt lakes, have evolved physiological mechanisms to cope with the salinity (Figure 8.2.3). Plant species that can survive high salinity are known as **halophytes** (from Greek 'halos', meaning 'salt' and 'phyton', meaning 'plant structure'). These plants use a variety of mechanisms to exclude or regulate the concentration of salt in their tissues.

FIGURE 8.2.3 *Arthrocnemum indicum* is a coastal halophyte adapted to living in a highly salty environment. This species can control salt levels by increasing water uptake.

Some physiological adaptations that plants have evolved to cope with salinity include transporting excess salt to vacuoles and old tissue, which avoids the toxic accumulation of salt ions in the cytoplasm, and excluding salt from the roots and leaves. Plants can exclude salt by:

- shedding leaves that are overloaded with salt
- excreting salt from salt glands
- pumping salt out of the roots
- controlling transpiration to avoid excess salt being delivered from the soil to the shoots
- balancing the rate of growth with the uptake of soluble ions to maintain a constant salt concentration in tissues
- increasing water uptake to dilute salt concentrations in tissues.

BIOFILE S

High and dry

The intertidal zone is the space on the coastline between the highest point of high tide and the lowest point of low tide. Species in the intertidal zone spend some of the time submerged in seawater, and some of the time exposed as the tides move in and out. Rock pools in the high intertidal zone—where only the highest of tides can reach—are rarely flushed with fresh seawater. These rock pools are extreme environments, exposed to direct sunlight, evaporation and wind, yet they are often full of life. Some species of seaweed thrive in such rock pools, and many types of seaweed outside the rock pools remain exposed to sunlight and wind for many hours each day without water.

One of the toughest seaweeds is the Australian native, *Hormosira banksii*, also known as Neptune's necklace or sea grapes (Figure 8.2.4). *Hormosira* tolerates hours out of water in direct hot sunlight and dry wind by secreting a thick, protective mucilage covering over its bubbles (vesicles), which are themselves filled with fluid. When the water in the rock pools evaporates, the salinity increases. *Hormosira* copes with this extra salty water by using salt bladders, as do many other halophytes. Salt bladders are modified epidermal (skin) cells on the surface of the leaf. Excess salt is pumped into this structure, keeping it away from more important leaf tissues, until the salt bladder pops and releases the excess salt into the environment. Due to its adaptations, this seaweed dominates the rocky intertidal environments of south-eastern Australia.

FIGURE 8.2.4 Physiological adaptations to changing conditions allow Neptune's necklace (*Hormosira banksii*) to survive and thrive in the challenging intertidal environment. Although it is regularly exposed to sunlight and hot, dry air for hours at a time, or trapped in high-salinity rock pools, this species successfully dominates the south-eastern Australian coastline.

BIOLOGY IN ACTION CCT

Adaptations of mangroves

Mangroves grow in the intertidal zone on shallow, muddy shores (Figure 8.2.5). This environment presents them with constantly changing and challenging conditions to which they need to adapt. Such conditions include:

- fluctuating salinity levels with the movement of the tide or from freshwater entering a tidal river
- lack of oxygen for their roots in the waterlogged soil
- boggy, unstable soil that makes anchorage difficult
- seed dispersal in an aquatic environment.

FIGURE 8.2.5 Mangroves grow in the constantly changing and challenging environment of the intertidal zone.

Getting rid of salt

Mangroves have three methods of ridding themselves of salt: exclusion, excretion and accumulation. Some mangroves exclude salt by actively pumping it out across membranes at their root surface. Other mangroves, including *Ceriops* (in Queensland) and *Avicennia* (which grows as far south as Victoria), also have salt-excreting glands on their leaves (Figure 8.2.6).

FIGURE 8.2.6 Salt crystals on a mangrove leaf. The salt is excreted in solution through specialised salt glands, and evaporation causes crystals to form. This physiological adaptation allows the plant to regulate internal salt concentration.

Specialised roots

Oxygen normally enters roots through **lenticels**, which are rough spots consisting of loose, corky tissue. Mangroves have evolved a range of aerial roots, all of which have lenticels. These aerial roots include peg roots, pneumatophores and stilt roots. Pneumatophores increase the surface area exposed to the air at low tide for maximum oxygen uptake. These types of aerial roots, together with cable roots that spread laterally, also help stabilise the plant in the soft mud (Figure 8.2.7). The cable roots have a mat of fine, hair-like roots that absorb nutrients and water.

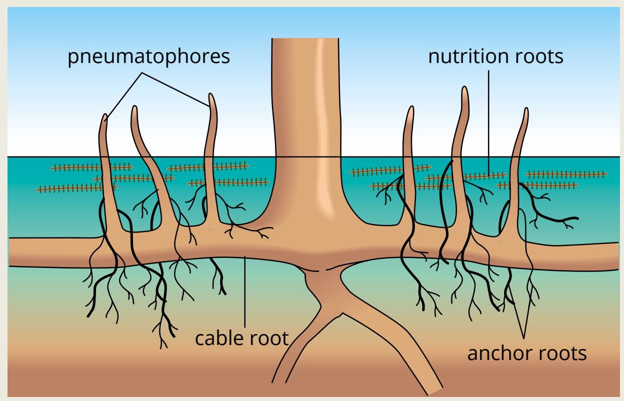

FIGURE 8.2.7 The structure of the root system of a typical mangrove plant, showing cable roots and pneumatophores.

Seed dispersal

The seeds of mangroves are buoyant and are adapted for dispersal by water. Some mangroves are **viviparous**. In plant science, 'viviparity' means that the seed germinates and the young plant starts to develop while still attached to the parent plant. When the germinating seed falls into the water, it already has a developing root system (Figure 8.2.8). This enables it to quickly anchor itself before it can be washed away by wave action.

FIGURE 8.2.8 Mangrove seeds have adaptations that enable them to disperse in their aquatic environment. In some species, the seeds already have a developing root system before they leave the parent plant. The seeds of most species can float in water.

PHYSIOLOGICAL ADAPTATIONS IN ANIMALS

Animals display an astounding diversity of physiological adaptations. With these adaptations, some species can overcome extreme conditions and exploit seemingly uninhabitable environments.

Examples of physiological adaptations in animals include:

- producing concentrated urine to conserve water in desert animals, such as the spinifex hopping mouse
- producing venom for prey capture or defence in most snakes, wasps, spiders, many marine animals and even some mammals, such as the platypus
- changing colour in response to sunlight to aid in thermoregulation in animals such as chameleons
- shivering to maintain body temperature when cold in endothermic animals, including humans.

Camouflage

Camouflage enables many organisms to blend in with their environment. This adaptation has many advantages, but it is particularly useful for avoiding predators or for capturing prey. One of the most amazing examples of camouflage is seen in the common octopus, *Octopus vulgaris* (Figure 8.2.9). It can change colour and texture to match its underwater environment, blending in with corals, sand or kelp to hide itself from predators and prey.

The common octopus has specialised colour-changing cells called chromatophores, which enable it to change colour to match its surroundings. Physiological mechanisms move pigment to and from the cells and change their reflective characteristics to produce the camouflage. In addition, tissues under the octopus's skin can create textures to match its environment.

FIGURE 8.2.9 The common octopus (*Octopus vulgaris*) uses specialised colour-changing cells called chromatophores to camouflage itself.

Evaporative cooling

Humans are one of the few animals that produce sweat to cool down. Adults can sweat up to 4 L/hr during vigorous exercise (Figure 8.2.10). Even when not exercising, this physiological adaptation plays an important role in thermoregulation through **evaporative cooling**. When warm sweat comes into contact with cooler air, it evaporates, carrying heat away and lowering body temperature. It does this through a process of energy (and therefore heat) transfer.

While sweating itself is not a common strategy, evaporative cooling occurs widely in the animal kingdom. Rather than sweating, many mammals employ evaporative cooling in the nasal passages, using secreted moisture to cool warm inhaled air. Other forms of evaporative cooling are behavioural in nature. You will learn about behavioural adaptations in Section 8.3.

FIGURE 8.2.10 Sweating is an important physiological adaptation in humans. It uses evaporative cooling to regulate the body's temperature and prevent overheating. Sweat is mostly water, but also contains lactic acid, urea and trace mineral elements, such as salt.

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Heat exchange for cooling

Heat exchange works in different ways in different animals. Desert ungulates (hoofed animals, from the Latin 'ungula', meaning 'hoof') such as the gemsbok oryx (*Oryx gazella*) use a **heat exchanger** to keep the brain cool (Figure 8.2.11a). If the oryx is dehydrated and can no longer afford to lose water, it stops sweating. This causes its body temperature to rise, sometimes as high as 43°C. If blood at such high temperatures entered the brain, the animal would die. To avoid this, the hot arterial blood travels through a smaller network of arteries before it enters the brain. This network of arteries is intertwined with another network of veins and smaller arteries. Because the arteries and veins are so close to one another, they can exchange heat. This network of veins and smaller arteries is called the **carotid rete system** (Figure 8.2.11b).

Animals that live in hot environments need physiological adaptations to efficiently exchange heat with their environment and keep their internal organs at a stable temperature.

The venous blood in the carotid rete system has travelled through the nasal sinuses and has been cooled using evaporative cooling in the nostrils. As this cooler blood from the nostrils passes in the opposite direction to the warmer blood from the body, the heat flows from the hotter blood to the cooler blood in the neighbouring network of blood vessels. This process is known as **countercurrent heat exchange**. This cools the blood entering the brain by several degrees, enabling the animal to survive in extreme heat and drought.

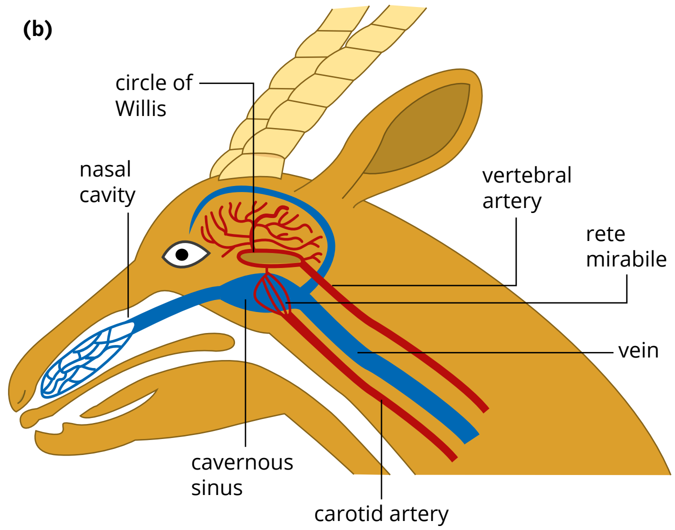


FIGURE 8.2.11 (a) A gemsbok oryx (*Oryx gazella*) in the Kalahari desert, South Africa. (b) The oryx's carotid rete system cools the hot arterial blood from the body before it enters the brain.

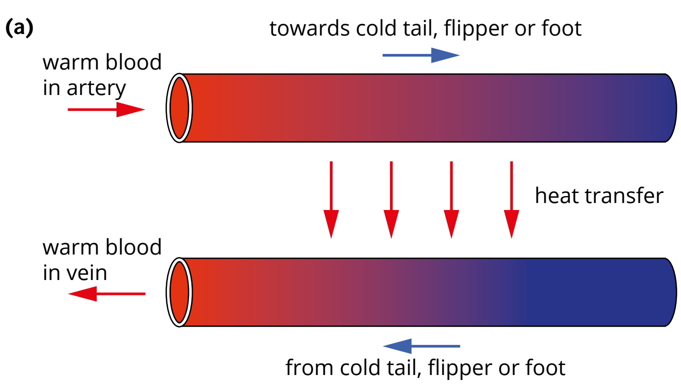
Heat exchange for heating

Countercurrent heat exchange also occurs in animals living in extremely cold climates, to reduce heat loss and maintain body temperature.

Penguins have heat exchangers in their flippers, feet and tails. These extremities have a relatively large surface area and are exposed to the cold, so they lose heat quickly. Blood from the penguin's feet flows back to the heart through veins close to the arteries. The warm blood in the arteries transfers heat to the veins to warm the blood moving back towards the heart, maintaining the penguin's body temperature (Figure 8.2.12). The blood travelling to the feet is cooled, minimising heat loss.

The diameter of the arteries flowing through the penguin's feet is also reduced to decrease the flow of blood to the extremities and further reduce heat loss. This is referred to as **vasoconstriction**. In this way, the cells in the feet receive oxygen and nutrients and remain warm enough to function, but less heat is lost to the environment.

Vasoconstriction occurs when the blood vessels are narrowed, reducing blood flow to an area and thus reducing heat loss. When the blood vessels widen, this is referred to as **vasodilation**.



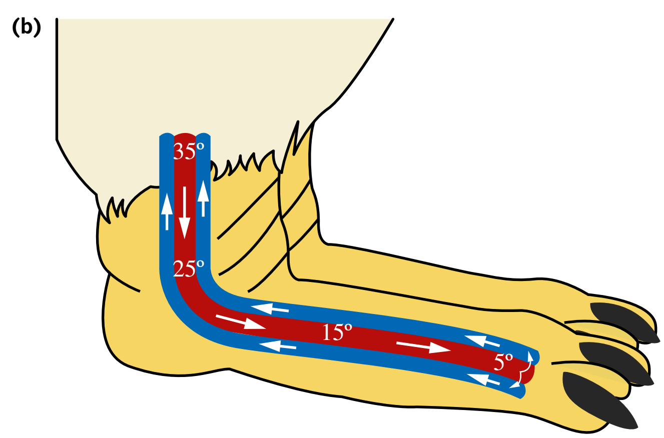


FIGURE 8.2.12 (a) The heat exchange mechanism in the cardiovascular system of penguins ensures that heat loss at the extremities is minimised, while the core body temperature is maintained. (b) The feet of the penguin have a large, exposed surface area and are therefore significant sites of heat loss.

Antifreeze proteins

Some fish that inhabit very cold water, such as the Antarctic cod (*Notothenia coriiceps*), manufacture a type of protein that prevents tissue from freezing. The antifreeze proteins, similar to those produced by plants, circulate in the blood of the fish and prevent the growth of ice crystals, keeping their blood liquid (Figure 8.2.13).

FIGURE 8.2.13 Antarctic cod (*Notothenia coriiceps*) use a variety of physiological mechanisms to survive extreme cold. One of these mechanisms is the production of antifreeze proteins.

Deep diving

Some diving mammals, such as the crab-eater seal (*Lobodon carcinophagus*), can stay submerged at depths of 430 m for more than 10 minutes (Figure 8.2.14). Diving mammals can store oxygen much more efficiently than other mammals. For instance, some seals can store 70% of their oxygen in their blood, while humans can store only 51%. The larger oxygen stores in diving mammals are made possible by their larger blood volumes, as well as increased levels of haemoglobin in the blood and myoglobin in muscles. Haemoglobin and myoglobin are proteins that bind to oxygen.

Diving mammals can also carry out anaerobic respiration (i.e., respiration in the absence of oxygen). They have a high tolerance for lactic acid build up, so their muscles can still function efficiently when oxygen stores have been depleted. These animals also have excellent control over their organs, reducing blood flow to those that are not needed for immediate survival, such as the digestive organs, while conserving precious oxygen for vital organs such as the heart and brain. This also reduces the work of the heart, slowing the heart rate dramatically and further conserving oxygen.

FIGURE 8.2.14 Crab-eater seals (*Lobodon carcinophagus*) can dive to depths of 430 m, remaining submerged for more than 10 min. They have a range of physiological adaptations that make this possible.

Torpor

Torpor is a physiological state in which the metabolic rate is lowered to save energy. This enables an organism to cope with environmental stresses, such as extreme cold or heat or decreased food or nutrient availability.

Torpor can occur over short or long periods. It involves both behavioural adaptations (retiring to a cave or seeking shelter and going to sleep) and physiological adaptations (slowing of the heart, breathing and metabolic rates).

A long period of torpor is often called dormancy, and can be triggered by many different stimuli, including day length (photoperiod), reduced food availability or a change in air temperature. **Hibernation**, **brumation** and **aestivation** are different forms of prolonged torpor. These often involve different metabolic processes and may have different triggers, but many triggers are shared by the three forms of torpor.

Hibernation

Hibernation is prolonged torpor during winter. Over summer and autumn, the animal builds up a thick layer of body fat that will provide it with energy during the hibernation period in winter. During hibernation, the animal can decrease its body temperature and heart rate to conserve energy. Hibernation occurs mostly in mammals, but some species of birds also hibernate. Bears, bats and squirrels are examples of animals that hibernate (Figure 8.2.15).

FIGURE 8.2.15 A pair of greater mouse-eared bats (*Myotis myotis*) hibernate in a cave.

Brumation

Brumation is similar to hibernation, but involves different metabolic processes. Reptiles such as snakes and lizards undergo brumation. It begins just before winter and can last between one and eight months. How long a reptile remains in brumation depends on the air temperature and the size and age of the animal. Once brumation begins, the reptile eats less or not at all, but wakes regularly to drink.

Aestivation

Aestivation is prolonged torpor in hot and dry conditions. Examples of aestivating animals are snails, frogs, crocodiles, tortoises, lungfish, some insects and some birds. This form of dormancy can be rapidly reversed when conditions change, but it can still continue for prolonged periods. Many aestivating animals move into shady and sheltered locations for the duration.

Green-striped burrowing frogs (*Cyclorana alboguttata*) are one example of a species that aestivates (Figure 8.2.16). These frogs inhabit semi-arid to arid regions of eastern Queensland and northern New South Wales. They spend up to nine months of the year in aestivation. During this time they live underground in small burrows and do not eat. They can reduce their metabolic rate by up to 80% during this time, allowing them to survive these underground periods just on their store of body fat.

FIGURE 8.2.16 The green-striped burrowing frog (*Cyclorana alboguttata*) aestivates underground for up to nine months of the year.

Bioluminescence

Bioluminescence is a physiological adaptation in which light is produced by an organism to attract attention, frighten enemies or lure prey. Bioluminescence is a form of chemiluminescence, which involves the release of light energy following a chemical reaction.

Fireflies, deep-sea fish and sea jellies are examples of bioluminescent organisms (Figure 8.2.17). They produce chemicals called luciferin (a pigment) and luciferase (an enzyme). The luciferin reacts with oxygen to create light. The energy system for bioluminescence is highly efficient, with no excess heat being produced. While most bioluminescent organisms produce light directly, some merely play host to bioluminescent bacteria, which live on the organism and produce light on their behalf.

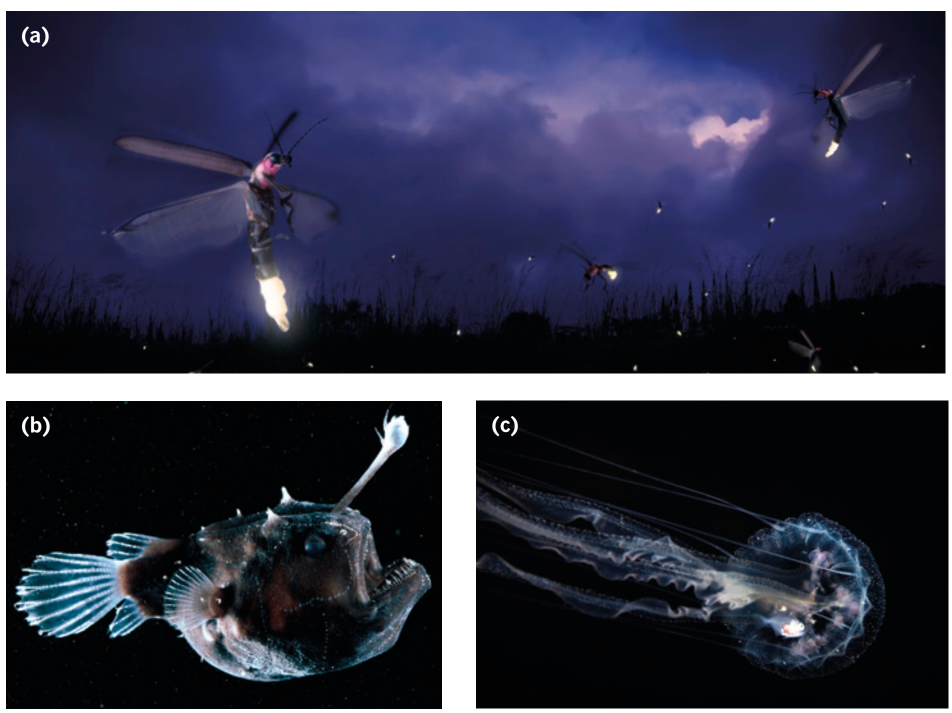


FIGURE 8.2.17 Bioluminescence occurs in many different organisms. It can be used for (a) communication and mate signalling, as in fireflies, (b) luring prey in deep-sea fish, as in anglerfish, and (c) startling and confusing predators, as in sea jellies.

BIOLOGY IN ACTION CCT IU

The soldiers that glowed in the dark

The Battle of Pittsburgh Landing

Over just two days during the spring of 1862, the Battle of Pittsburgh Landing during the American Civil War saw more than 16,000 soldiers wounded and more than 3000 killed. Medics were not prepared to deal with the overwhelming number of men that needed medical attention, and untreated wounds contaminated with dirt and shrapnel were the perfect breeding ground for bacteria. The soldiers' immune systems were weak after months of poor diet and living conditions, and infections soon ravaged the camps.

During this time, little was understood about the biology of microorganisms, and antibiotics had not been developed. Infections that are easily treated today took many soldiers' lives. As soldiers waited for days in the muddy fields for medics to help them, some of them noticed something strange: as night fell, their wounds began to glow. Even more peculiar, those with glowing wounds healed faster and had a better chance of survival. The apparent healing powers of the strange illumination earned it the name Angel's Glow.

The science of the glowing soldiers

The cause of Angel's Glow remained unknown until 139 years later, when 17-year-old Bill Martin visited the battlefield in 2001. When he learnt about the glowing wounds, he asked his mother (a microbiologist researching luminescent bacteria) what might have caused it. She told Bill to do an experiment to find out. So Bill and his friend, Jon Curtis, investigated a bioluminescent bacterium called *Photorhabdus luminescens*. They thought that the life cycle of the bacterium might hold clues to the cause of the soldiers' glowing wounds.

P. luminescens bacteria live in the gut of parasitic worms called nematodes. Because the nematode hosts the bacteria and they both benefit from this relationship, they are referred to as symbionts. The nematodes burrow into the bodies of insect larvae living in the soil and move into their blood vessels (Figure 8.2.18). Once inside the larva, the nematode ejects the bacteria. The bacteria begin to produce toxins that kill the insect larva, along with antibiotics that kill any other microorganisms living inside the insect larva.

P. luminescens emits a soft blue glow while they, and their nematode host, consume the remains of the insect larva. The bacteria secrete enzymes that hydrolyse (break down) the larval corpse. The glowing bacteria in the insect corpse attract other insects, making the search for the next host easier. Once the larva has been consumed, the nematode ingests the bacteria again, allowing them to recolonise the worm's gut and hitch a ride to the next host (see Figure 8.2.19).

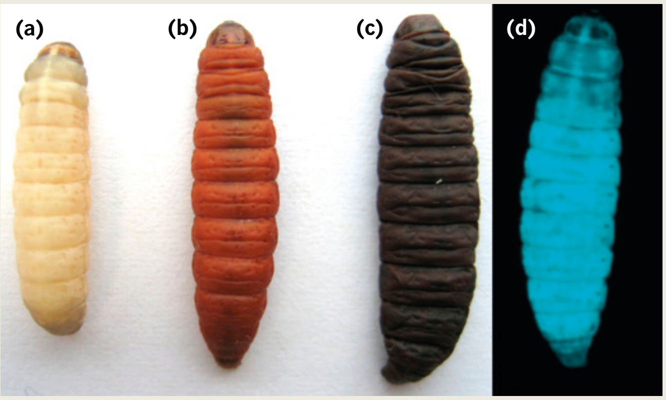


FIGURE 8.2.18 Larvae of the greater wax moth (*Galleria mellonella*) infected with *Photorhabdus luminescens*: (a) not infected; (b) 24 hours after infection; (c) 48 hours after infection; and (d) bioluminescence in a larva caused by infection with *P. luminescens*.

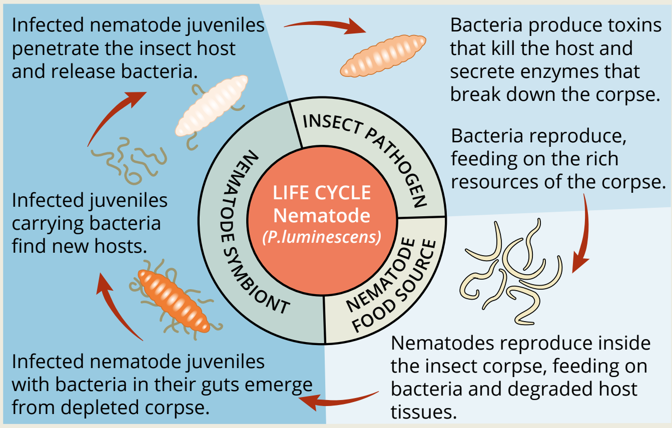


FIGURE 8.2.19 Life cycle of the bioluminescent bacteria *Photorhabdus luminescens*

Historical records of the battle revealed that the weather and soil conditions at that time would have been ideal for *P. luminescens* and the nematodes. Although human body temperatures are not ideal for the bacterium, Bill and Jon calculated that the cold overnight temperatures that the soldiers were exposed to would have lowered the soldiers' body temperatures enough to be suitable for the bacterium.

Bill and Jon hypothesised that the host nematodes colonised the soldiers' wounds from the soil. Neither *P. luminescens* nor the nematodes are particularly infectious to humans, and would have eventually been destroyed by the soldiers' immune systems. However, antibiotics produced by the bacteria would have killed any pathogenic bacteria in the soldiers' wounds, helping them avoid infection. *P. luminescens* not only made the soldiers glow, but also may have saved their lives.

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Systems biomimicry

Systems biomimicry involves mimicking processes that work together to manage materials or energy. Systems biomimicry is a relatively recent development that is being used to solve engineering problems: particularly those involving energy. For example, designers looking to increase the efficiency of wind turbines were inspired by the movement of humpback whale flippers through the water. Their fins have bumps called tubercles, which improve lift and reduce drag.

Portcullis House, United Kingdom

The architects who designed Portcullis House, a seven-storey building in London, created an air-conditioning system modelled on termite mounds. The temperature of termite mounds is maintained within a range of one degree without the use of energy, using a series of funnels and cool, moist underground chambers. The outside air flows into the funnels, is cooled in the chambers and distributed throughout the mound. Warm air is then released through the top of the termite mound (Figure 8.2.20a).

The heating and cooling system in Portcullis House uses a series of chimneys and vents (Figure 8.2.20b) that allow fresh air to enter the building. This air is warmed in winter by solar radiation, and cooled in summer by groundwater. This system has been so effective that there is no need for traditional air conditioning or heating. Portcullis House uses only 25% of the energy used in traditional office buildings.

(a)

(b)

FIGURE 8.2.20 (a) A large termite mound in Kakadu National Park, Australia. The temperature inside the termite mound is maintained within a one-degree range. (b) The design of the passive heating and cooling system in Portcullis House in London was inspired by the temperature-regulation system in termite mounds.

8.2 Review

SUMMARY

- Physiological adaptations pertain to the functioning of the animal at biochemical, cellular, tissue, organ, system and whole organism levels.
- Examples of physiological adaptations of plants are:
  - CAM (crassulacean acid metabolism) photosynthesis
  - frost tolerance
  - salinity tolerance
  - drought tolerance.
- Examples of physiological adaptations of animals include:
  - the ability to produce concentrated urine
  - countercurrent heat exchange mechanisms
  - dormancy, hibernation, torpor and aestivation
  - production of venom or poisons
  - ability to withstand high temperatures
  - sweating
  - shivering to maintain body temperature
  - production of antifreeze proteins to prevent freezing.

KEY QUESTIONS

1. Describe a physiological adaptation, listing two examples each for animals and plants. Explain how these adaptations enable animals and plants to survive in their environment.
2. The next two questions refer to the crassulacean acid metabolism (CAM) pathway.
   - **a** What is the CAM pathway? How does it differ from the normal photosynthetic process?
   - **b** No adaptation is without some cost to the organism. What are some of the disadvantages of the CAM pathway? Why would this be a poor strategy in a damp environment?
3. Why is excessive soil salinity a problem for plants? List two physiological adaptations that allow plants to survive in highly saline environments.
4. Sweating is a common physiological adaptation. How does it work? Why is sweating an advantageous strategy?
5. What is countercurrent heat exchange? Describe this mechanism and explain how it can be used to either increase or decrease heat loss. You can create a diagram using examples from the text, or come up with your own.
6. What is meant by the terms 'vasodilation' and 'vasoconstriction'? Explain how these two processes function to regulate body temperature.
7. Why is bioluminescence such a favourable strategy for communication in nocturnal animals and in the deep sea?

8.3 Movement and behavioural adaptations

Movement and **behavioural adaptations** are actions that an organism takes to improve survival or reproduction. Plants have movement adaptations that allow them to move toward favourable conditions and away from unfavourable conditions. In animals, behaviours may be learnt, such as the use of tools in chimpanzees and crows, or instinctive, such as a spider spinning a web. The behaviour of animals can be incredibly complex, but even the simplest behaviours can be critical for the survival of individuals and populations.

ADAPTATIONS FOR MOVEMENT IN PLANTS

When a plant cell takes in water through osmotic regulation, it cannot expand, due to the rigid cell wall. This increases the internal pressure of the cell, and is referred to as turgor pressure.

Plants can grow or move towards or away from positive or negative conditions in their environment.

Although plants do not have muscles or a nervous system like animals do, they can still move in response to their environment. In most cases, the mechanisms for plant movement are controlled by **hormones** or **turgor** pressure, both of which are physiological processes. Therefore, although the end results can share some similarities with the behavioural adaptations of animals, we do not usually refer to plant movements as 'behavioural'.

Plants that are capable of rapid movement rely on internal changes in turgor. Changes in turgor are usually initiated by contact with objects outside the plant. The cells involved are in the parenchyma tissue of the cortex, or specialised swellings (pulvini) at the base of leaves or leaflets. Some movements may be very fast, occurring in less than a second.

Plants can undergo two types of movement in response to environmental stimuli. One is called **tropism** and the other is called **nastic movement**.

Tropism

FIGURE 8.3.1 The growth of these seedlings towards the light is an example of tropism.

Tropism is plant growth in response to an environmental factor, such as gravity, light or water (Figure 8.3.1). The response depends on the direction of the **stimulus**. The plant will either grow towards the stimulus (positive tropism) or away from the stimulus (negative tropism). Tropisms are controlled by plant hormones, such as auxin, gibberellin, ethylene and cytokinin.

Types of tropisms include:

- **phototropism**—growth in response to light
- **geotropism** or **gravitropism**—growth in response to gravity
- **chemotropism**—growth in response to chemicals
- **thigmotropism**—growth in response to touch
- **hydrotropism**—growth in response to water concentration.

Phototropism

Phototropism in seedlings is an elegant example of movement in plants, and it owes its effectiveness to a group of hormones called **auxins**.

Auxins are produced at the tip of the plant, and function by encouraging elongation in plant cells. In darkness, they are spread evenly down both sides of the stem, but the presence of light interrupts their flow. When the light is on one side of the seedling, the auxins become concentrated on the dark side—the side facing away from the light—so that the cells on that side of the plant become elongated. However, the cells on the side facing the light contain less auxin, and do not elongate. Therefore, the dark side of the seedling becomes longer than the light side, causing the seedling to bend towards the light (Figure 8.3.2).

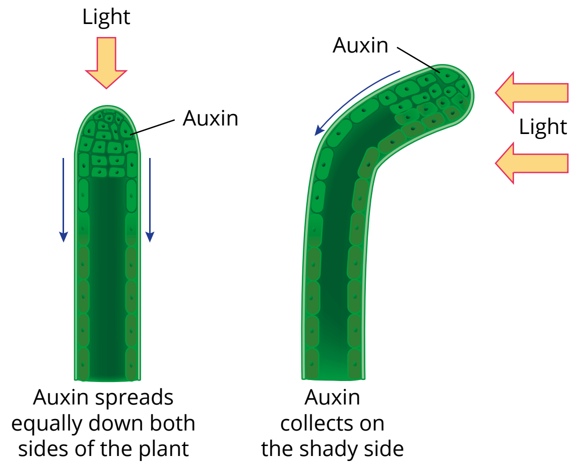

FIGURE 8.3.2 A group of plant hormones called auxins allow plants to grow towards light (phototropism). They cause the dark side of a seedling to grow faster than the light side, causing the seedling to bend towards the light.

Nastic movement

Nastic movement is a movement of plant tissue in response to an environmental stimulus (but not in the direction of the stimulus). This allows a plant to adapt to changes in its environment by changing its orientation. Some nastic movements in plants are:

- **thigmonasty**—movement in response to touch
- **photonasty**—movement in response to a change in light intensity
- **thermonasty**—movement in response to a change in temperature.

Thigmonasty

Thigmonastic movements include the rapid opening and closing of plant parts in response to touch, such as those observed in the Venus fly trap, *Dionaea muscipula* (Figure 8.3.3).

The Venus fly trap is a carnivorous plant that is adapted to low levels of nitrogen in the soil. It obtains nitrogen by trapping prey such as flies, which it attracts by secreting a sweet sap. When a fly touches the tiny hairs (mechanosensors) on the leaves, an electrical signal is sent to the centre of the trap. This signal opens pores in the trap's lower layer of cells, allowing water to rush in from the cells in the upper layer of the trap. The rapid change in pressure (turgor) causes the cells on the lower side of the trap to expand, forcing the trap to snap shut, trapping the fly inside. Enzymes released by the plant then digest the insect. About one-third of the ATP in the cells is used in each movement. This is why after repeated touches, a leaf will not respond until its energy reserves have been replenished.

FIGURE 8.3.3 The Venus fly trap (*Dionaea muscipula*) uses mechanosensors (hairs) on the leaf surface to trigger cell pores to open in the lower side of the leaf. Water rushes into these cells, causing them to expand and forcing the trap to close.

FIGURE 8.3.4 A bloodroot plant (*Sanguinaria canadensis*) displaying photonastic movements on a cloudy morning. In low light, this plant closes its leaves and flowers.

Photonasty

The flowers and leaves of many plants respond to changes in light intensity, opening during the day and closing at night or on cloudy days (Figure 8.3.4). This is an example of photonasty.

Thermonasty

An example of thermonastic behaviour is the opening and closing of tulips in response to air temperature. The petals open as the air temperature rises and close when the temperature falls. This behaviour allows the pollen to be exposed only in warmer weather, when pollinators are more likely to visit the flower, and protects it during cooler weather. As in the thigmonastic movement of the Venus fly trap, this movement is a result of turgor pressure.

BIOFILE CCT

Trigger plant

Trigger plants (*Stylidium* species) have one of the fastest movements in the plant world. The flowers have a structure called a column (the trigger), where the male anthers as well as the female stigma are located. When triggered by the touch of an insect, the column flicks back against the insect's body, depositing or picking up pollen from its back (Figure 8.3.5a). This mechanism is a form of thigmonasty and ensures cross-pollination between plants. Some other plants have similar mechanisms in which the stamens are pulled in towards the centre of the flower, usually hitting the pollinator (Figure 8.3.5b).

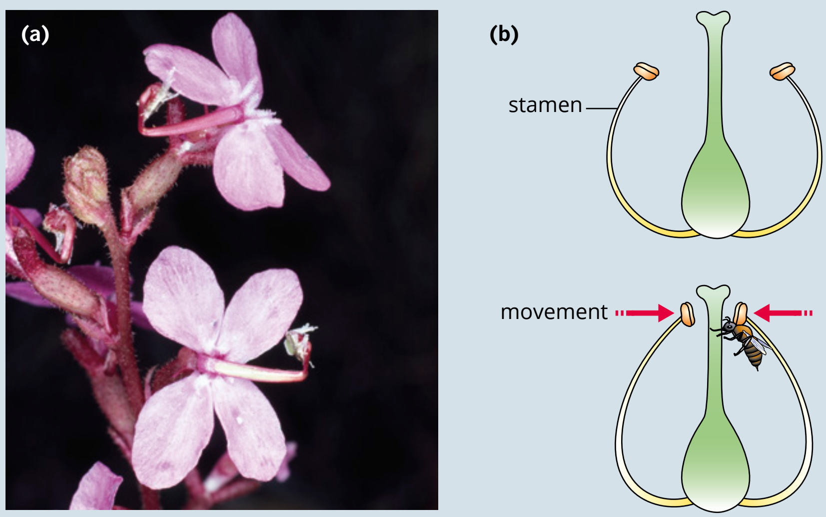

FIGURE 8.3.5 (a) The column of a trigger plant flower lies flat before it is triggered (top flower), and flips up to a vertical position after it has been triggered (bottom flower). (b) In some plants, the touch of a pollinating insect can cause the stamens to the pulled rapidly inwards, depositing pollen on the insect.

BEHAVIOURAL ADAPTATIONS OF ANIMALS

Behavioural adaptations in animals that help them to survive in extreme environmental conditions include:

- seeking or leaving shade or shelter
- evaporative cooling to lower temperature
- huddling to maintain body temperature
- migration.

Animals have many behavioural adaptations to respond to changes in their environment.

Seeking or leaving shade or shelter

Many desert animals regulate the rate of heat exchange with their environment by seeking shade when the heat is too great and leaving it when temperatures fall. The central netted dragon (*Ctenophorus nuchalis*) is a good example of such a behavioural adaptation. To raise its body temperature, the lizard emerges from under a rock and basks in the sunshine, spreading itself out at right angles to the Sun's rays. To lower its body temperature or reduce the rate of increase in body temperature, the lizard orientates its body parallel to the Sun's rays, minimising the exposed surface area, or simply retreats beneath a rock or into a burrow (Figure 8.3.6).

FIGURE 8.3.6 The central netted dragon (*Ctenophorus nuchalis*) has adapted its behaviour to desert conditions, regulating its temperature throughout the day by seeking shade or basking in sunlight.

Some animals, such as desert snakes and tortoises, adopt nocturnal behaviour during summer to prevent overheating. They move only in the cooler evening, avoiding the extreme heat of the day. Animals may also seek shelter to increase their body temperature when it is cold or windy.

Evaporative cooling

Many land animals use evaporative cooling to lower their body temperature by releasing heat into the environment. Although this is a physiological adaptation (as explained in Section 8.2), it is often achieved by behavioural adaptations, such as:

- panting or licking limbs
- spraying water on the body
- mouth gaping
- wallowing in mud or water
- gular fluttering
- urohydrosis.

Panting or licking

Panting or licking limbs enable animals to release heat effectively using evaporative cooling. For example, kangaroos lick their paws, and animals such as dogs, gazelles and foxes pant. The fennec fox (*Fenecus zerda*) has been observed panting at a rate of 690 times per minute after chasing prey.

FIGURE 8.3.7 A female African elephant (*Loxodonta africana*) splashes water over her body, making use of evaporative cooling to control her body temperature.

FIGURE 8.3.9 A pig wallows in mud to cool down.

FIGURE 8.3.10 Emperor penguin chicks (*Aptenodytes forsteri*) huddle together for warmth.

The rate of panting is proportional to the amount of air flowing over the tongue. If animals can flatten their tongue to increase its surface area while increasing their panting rate, then the cooling effect is greater. Sometimes even penguins have to pant. In warmer weather, they also hold their flippers out of the water so that both surfaces are exposed and can release heat via evaporative cooling.

Spraying water

Elephants commonly spray water on their body to cool off via evaporative cooling (Figure 8.3.7). Mud remaining on the elephant's skin provides protection against solar radiation. Water spraying behaviour is also used by many other animals.

Mouth gaping

Mouth gaping is seen in many animals, such as crocodiles and alligators (Figure 8.3.8). This behaviour allows air to move across the moist surface of an open mouth. Evaporative cooling from the membranes inside the mouth reduces the temperature of blood being supplied to the brain.

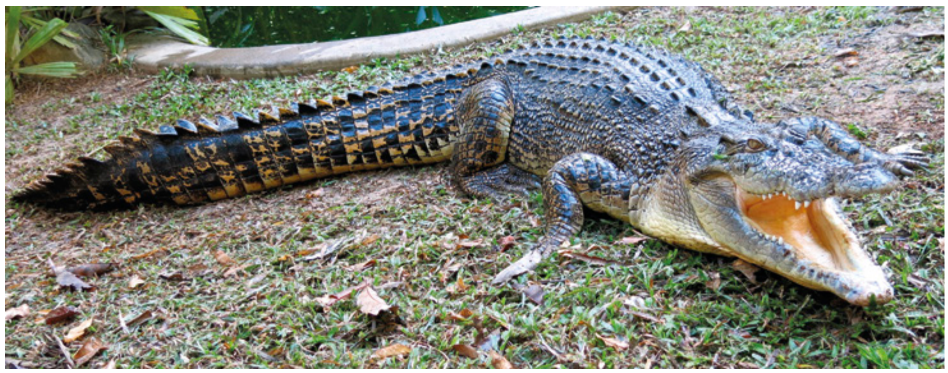

FIGURE 8.3.8 A saltwater crocodile (*Crocodylus porosus*) opens its mouth to allow water to evaporate from its moist tongue.

Wallowing in mud or water

Wallowing in mud or water is a very common behaviour. Animals such as pigs, elephants, rhinoceroses and deer wallow in wet mud to cool the skin, while animals such as hippopotamuses, tapirs, bison, horses and cattle wallow in water.

Wallowing in mud has many advantages for animals, including skin maintenance, camouflage, parasite control, protection from solar radiation and social play. One of the more common reasons is thermoregulation. Like sweating, the evaporation of the water in the mud cools the animal's skin by carrying heat away from the body. It can cool the animal's body by up to 2°C, making it more efficient than sweating. Wallowing in mud has an advantage over water too; the water in the mud evaporates more slowly than water alone, keeping the animals cooler for longer (Figure 8.3.9).

Gular fluttering

Gular fluttering is a cooling behaviour in which birds flap membranes in their throat to increase evaporation from the moist buccal (mouth) region. As the air temperature increases, birds increase the amount of gular fluttering.

Urohydrosis

Urohydrosis is a cooling behaviour exhibited by some birds, including vultures and storks. They urinate on their legs, creating an evaporative cooling effect.

Huddling

Many animals, such as penguins, huddle to cope with cold temperatures (Figure 8.3.10). Thousands of emperor penguin chicks may huddle together for warmth in the spring, when they begin to develop their adult plumage. By huddling, penguins decrease the surface area of the group exposed to the harsh environment. They continually rotate the animals on the outside, each taking a turn in the freezing cold winds.

Migration

Some animals move extremely long distances each year to inhabit a different area. This type of seasonal pattern of relocation is known as **migration**.

The purpose of migration is usually to seek better food availability, to move to a better site for breeding, or to find suitable climatic conditions. Birds navigate their migratory paths using the position of the Sun and Moon, as well as topographical details and cues from Earth's magnetic field. Migration is an **innate behaviour** prompted by cues from the environment, such as the length of daylight. These cues are closely coordinated with an animal's biological clock and trigger biological responses, such as increased feeding before migration.

Migration can occur on a number of different scales. For example, humpback whales of the Southern Hemisphere migrate vast distances on an annual basis. They spend the warmer southern months in Antarctic waters, feeding on krill blooms. In autumn, they migrate to warmer waters in the tropical Pacific for calving and breeding. African elephants (*Loxodonta africana*) also migrate over long distances, travelling more than 80 km annually in search of food resources (Figure 8.3.11).

By contrast, zooplankton in all the oceans of the world exhibit what is called diurnal vertical migration. This means that they migrate daily from the bottom of the ocean to the surface. At sunset, zooplankton rise to the surface to feed on the phytoplankton that live in the surface waters. However, during the day, the zooplankton would be visible to predators, so they return to the depths at sunrise. In terms of biomass (the total mass of all the organisms involved), this is the largest mass migration in the world.

FIGURE 8.3.11 African elephants (*Loxodonta africana*) migrate over long distances every year in search of food.

WS 3.3

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Process biomimicry

Process biomimicry involves the imitation of behaviours or a series of operations. For example, engineers and mathematicians are developing algorithms based on the communication behaviour of ants and bees. Using this approach, control boxes that attach to electrical appliances have been developed to communicate with one another and monitor and regulate the appliances' energy use (Figure 8.3.12). In a way similar to beehive communication systems, signals are sent out across the whole network of appliances, and energy management decisions are made according to the status of the entire system.

FIGURE 8.3.12 (a) This wireless energy management device communicates with household appliances to monitor and regulate energy use. The inventors of the device were inspired by the way that social insects, such as bees, communicate. (b) Bees have complex communication systems to manage work and energy use within the hive.

+ ADDITIONAL

Life without photosynthesis

Most ecosystems on Earth derive their basic energy from sunlight. This basic level of the food web starts with photosynthesis. Primary producers, such as land plants and microscopic phytoplankton, use sunlight to manufacture sugars so that they can grow and reproduce. Secondary producers (usually animals) feed on the primary producers—and on one another—so that they can grow and reproduce.

However, life does exist in places without light, such as the deep sea. Although most organisms in the deep sea feed on 'marine snow'—the detritus (debris) that drifts down from the richer surface waters—some pockets of life exist entirely independent of the Sun's energy and the photosynthetic pathway. Such organisms have been found in deep ocean hydrothermal vents.

Hydrothermal vents are small cracks in Earth's crust. The vents form in volcanically active areas, usually along mid-oceanic ridges, where pressure in the crust causes a fissure. Their average depth is around 2100 m below the surface. Superheated fluid emerging from the vents can heat the water from 60°C to well over 400°C. This is an abrupt shift from the ambient water temperature, which is around 2°C. The water is also laden with minerals and inorganic compounds from deep within the crust.

The existence of hydrothermal vents was confirmed in the 1960s. For a long time, researchers expected that these hostile and extreme environments would be devoid of life. However, in 1977, a team of scientists discovered a surprisingly rich and diverse ecosystem clustered around a hydrothermal vent.

The hydrothermal vent provides minerals and energy that feed specially adapted bacteria and archaea. Instead of using energy from sunlight, these organisms use the energy released from the breakdown of compounds such as hydrogen gas, hydrogen sulfide or methane. Their metabolism is therefore chemosynthetic, rather than photosynthetic.

Taking their energy from the vents, the microbes form thick mats that other organisms can then feed upon. Highly heat-tolerant tubeworms grow near the vents (Figure 8.3.13a), providing further food resources as well as structural shelter for well-adapted crabs, fish (Figure 8.3.13b) and numerous other animals. A thriving ecosystem exists in a place that was never expected to support life.

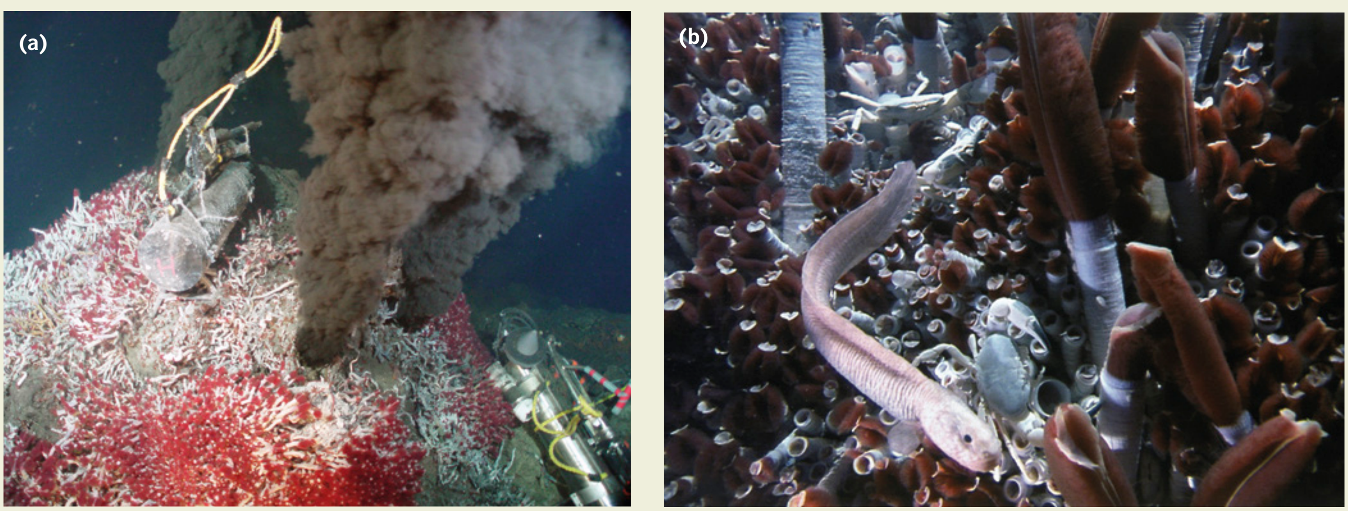


FIGURE 8.3.13 (a) Scientists place monitoring equipment around a black smoker hydrothermal vent. The white and red structures are a community of large, heat-tolerant tubeworms. (b) Hydrothermal vents also support vertebrate life, such as this heat-tolerant fish.

8.3 Review

SUMMARY

- A behavioural or movement adaptation is how an organism acts or moves in response to its environment.
- Examples of movement adaptations in plants include:
  - tropisms—movements towards or away from a particular stimulus
  - nastic movements—movements in response to a stimulus, but not necessarily towards or away from that stimulus.
- Types of tropisms are:
  - phototropism—movement towards or away from light
  - geotropism or gravitropism—movement towards or away from Earth
  - chemotropism—movement towards or away from a chemical substance
  - hydrotropism—movements towards or away from water
  - thigmotropism—movement towards or away from touch.
- Types of nastic movements are:
  - photonasty—movement in response to light
  - thigmonasty—movement in response to touch
  - thermonasty—movement in response to temperature.
- Examples of behavioural adaptations of animals include:
  - huddling for warmth
  - evaporative cooling behaviours, such as panting, licking skin, wallowing and gular fluttering to lose heat
  - seeking shade or sunlight
  - nocturnal activity
  - burrowing
  - migration.

KEY QUESTIONS

1. Describe a movement adaptation, listing two examples for plants. Explain how these adaptations enable plants to survive in their environment.
2. Why don't we use the term 'behavioural' to describe plant movement?
3. What is the difference between tropism and nastic movements in plants?
4. Describe a behavioural adaptation, listing two examples for animals. Explain how these adaptations enable animals to survive in their environment.
5. Explain how evaporative cooling works to regulate heat exchange. Humans take a physiological approach to evaporative cooling, by sweating. Many animals employ a behavioural approach instead. Give two examples of animals that use evaporative cooling through a behavioural adaptation.
6. Migration is a complex behavioural adaptation exhibited by many animals. Choose an organism that migrates regularly. Briefly describe the scale and purpose of the migration, and explain how this is an advantageous behaviour.
7. Plants usually move so slowly that we can't see it with the naked eye, but stop-motion photography and video allows us to see what is happening over long time periods. Find one video showing an example of tropism in a plant and one showing an example of nastic movement in a plant and watch them carefully. Which sort of tropism (e.g. phototropism, geotropism) and nastic movement (e.g. photonasty, thigmonasty) are being shown? How does the movement help the plant survive?

8.4 Forming a theory: Charles Darwin and natural selection

We now accept the theory of evolution by natural selection as the best explanation for the origin of species and how they adapt to their environment. However, people once believed that all organisms were created in their current forms. By the 18th and 19th centuries, many people were no longer satisfied with this explanation. The question of how so many different species came to exist, and how they were so well adapted to their particular environment and lifestyles, puzzled many great thinkers of the time.

Several different scientists tackled the question and contributed to the model of **evolution** we now accept (see Additional box on p. 372). But it was Charles Darwin (1809–1882) who most famously publicised the principles of evolution by natural selection. The story of Darwin's discoveries and the formation of his theory is one of the most important stories in the history of scientific thinking.

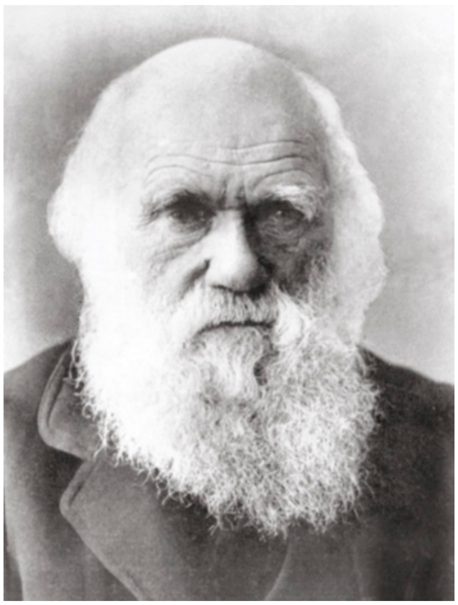


FIGURE 8.4.1 Charles Darwin was a key scientist in the development of the theory of evolution.

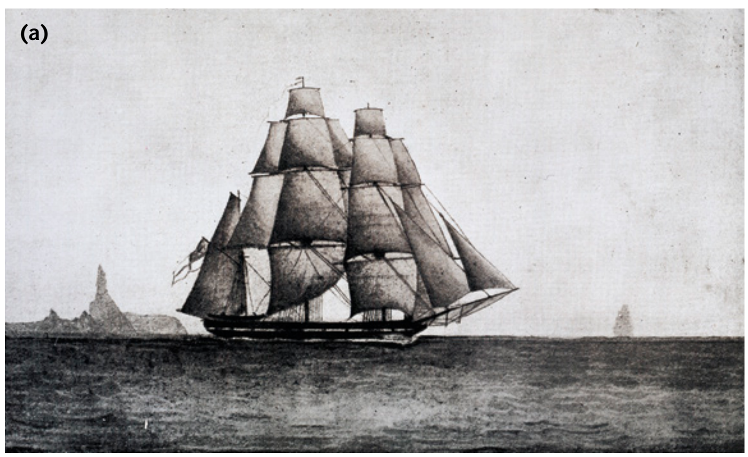
CHARLES DARWIN AND THE VOYAGE OF THE HMS BEAGLE

Charles Darwin (Figure 8.4.1) was an English naturalist who sailed on the HMS *Beagle*. He made numerous biological and geological observations on the voyage. He also collected specimens from every location that the ship visited. Many of these specimens can still be seen in museums around the world (Figure 8.4.2).

FIGURE 8.4.2 Many of the specimens collected by Darwin can be viewed in museums around the world.

The second voyage of the HMS *Beagle* (Figure 8.4.3a) was nearly five years in length. Departing England in December 1831 and returning in October 1836, the voyage surveyed South Africa, large portions of southern America, Tahiti, Australia, New Zealand and, most famously, the Galápagos Archipelago (Figure 8.4.3b).

(a)



(b)

FIGURE 8.4.3 (a) Charles Darwin travelled as a naturalist on the HMS *Beagle*. On this voyage, he made many of the initial observations that would inform his theory of evolution by natural selection. (b) The HMS *Beagle* travelled through the tropical Indo-Pacific and much of the Southern Hemisphere on its influential second voyage from 1831 to 1836.

During the voyage, Darwin—a young man at the time—collected his most crucial initial observations. These observations would later influence the formation of his theory, which he would neither publish nor publicise for many years. Like any good scientist, Darwin took extensive notes on his observations. By reading these notes, we can follow the progress of his ideas. These ideas eventually came together to form his theory of evolution by natural selection, which Darwin published in his book, entitled *On the Origin of Species by Means of Natural Selection* (1859).

It is commonly thought that Charles Darwin discovered evolution. Actually, among many scientists, evolution was an accepted fact throughout his life. Darwin's significant contribution was to explain the mechanism by which it works.

Finches of the Galápagos Islands

When Darwin first examined the variety of birds found across the Galápagos Islands, he had no idea that most of them were finches and belonged to the same family (Thraupidae). It was only when he returned to England that John Gould, the famous ornithologist (bird specialist), demonstrated that these species were slight variations of each other. Some, such as the warbler finch, had narrow pointed beaks; others, such as the medium ground finch, had strong wide beaks (Figure 8.4.4).

Darwin used John Gould's observations of beak size and length, along with his own records of the types of food available on each island, to develop his theory of evolution by natural selection. The differing forms of the beaks were the **traits** (inherited physical characteristics) altered by natural selection.

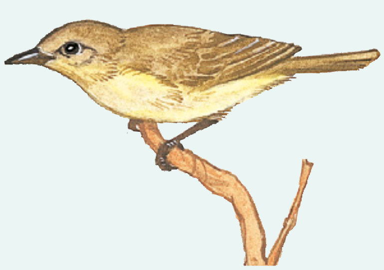
Each island of the Galápagos Archipelago has a different environment, with different foods available: from cacti to large seeds. These environments provided a variety of **selection pressures** for birds that migrated between the islands. For example, if a warbler finch, which has a slender beak, migrated to an island with only large seeds and few insects, it would struggle to find enough food to eat, resulting in selection pressure and adaptation to the local environment over time. Table 8.4.1 shows some of the Galápagos finches that diverged from a common ancestor and adapted to their particular environment and **ecological niche**.

The term 'niche' is used to describe the particular lifestyle of an organism. A niche includes the environment of an organism and their role in their environment, such as the food they eat, how they reproduce and their interactions with other organisms.

FIGURE 8.4.4 (a) Medium ground finch (*Geospiza fortis*), (b) warbler finch (*Certhidea olivacea*), and (c) common cactus finch (*Geospiza scandens intermedia*) are all species of finches that are only found on the Galápagos Islands. These species all belong to the family Thraupidae, but each have different physical characteristics because they have adapted to different environments and feeding niches.

The famous example of the Galápagos finches is significant on several levels. First, it is a prime example of **adaptive radiation**, when a single species evolves into several species by adapting to the requirements of different environmental niches (Table 8.4.1). Second, Darwin did not realise how important his observations would be at the time, but his collection of data would turn out to support his theories later on. This is often the case in science. Finally, without Gould's input on the relatedness of the birds, he would never have understood their significance. Scientists often rely upon one another's expertise to place data in context and draw reliable inferences.

TABLE 8.4.1 Different species of finches that have resulted from adaptive radiation to different feeding niches on the Galápagos Islands

Type of finch	Genus and species	Beak type	Environment/food type
ground finch 	Nine species in genus: • common cactus finch (*Geospiza scandens*) • Española ground finch (*Geospiza conirostris*) • Genovesa cactus finch (*Geospiza propinqua*) • Genovesa ground finch (*Geospiza acutirostris*) • large ground finch (*Geospiza magnirostris*) • medium ground finch (*Geospiza fortis*) • sharp-beaked ground finch (*Geospiza difficilis*) • small ground finch (*Geospiza fuliginosa*) • vampire ground finch (*Geospiza septentrionalis*)	• crushing beak, species specialise in eating different-sized food • largest finch, with large beak • longer more pointed beak	• widespread • live in coastal areas and lowlands, feeding on the ground • seeds • cactus
tree finch 	Five species in genus: • small tree finch (*Camarhynchus parvulus*) • medium tree finch (*Camarhynchus pauper*) • large tree finch (*Camarhynchus psittacula*) • mangrove finch (*Camarhynchus heliobates*) • woodpecker finch (*Camarhynchus pallidus*)	• grasping beak • woodpecker finch uses tools—twigs and cactus spines • smallest tree finch with small beak	• live in forests, feeding in trees • grubs • insects
vegetarian finch 	Only one species in genus: • vegetarian finch (*Platyspiza crassirostris*)	• a large bird with a very heavy beak used to pull buds from plants	• lives in forests and feeds on plants, eating fruit, buds and soft seeds • absent from outlying islands
warbler finch 	Two species in genus: • green warbler finch (*Certhidea olivacea*) • grey warbler finch (*Certhidea fusca*)	• slender beak • searches for food among leaves and branches	• widespread species occurring on all of the islands • only feeds on insects • sometimes catches insects when flying

Australian flora and fauna

Darwin visited Australia in January 1836, in the latter part of his journey. He was struck by the apparent strangeness of the Australian landscape.

"A little time before this," he wrote in his diary, "I had been lying on a sunny bank and was reflecting on the strange character of the Animals of this country as compared to the rest of the World."

By this time, Darwin had already observed that animals that occurred in neighbouring environments bore a strong resemblance to one another, regardless of whether or not those environments were similar. This puzzled him. In *On the Origin of Species*, Darwin wrote:

"Why should the species which are supposed to have been created in the Galápagos Archipelago, and nowhere else, bear so plain a stamp of affinity to those created in America? There is nothing in the conditions of life, in the geological nature of the islands, in their height or climate, or in the proportions in which the several classes are associated together, which resembles closely the conditions of the South American coast: in fact there is a considerable dissimilarity in all these respects."

In other words, the species of the Galápagos Islands and South America appeared to be similar in spite of facing very different environmental challenges. We now know that this is because they all shared a recent **common ancestor** before evolving their different adaptations.

During his visit to Australia, Darwin observed several platypuses playing in a river (Figure 8.4.6a). He noted that they occupied a similar environmental niche to the English water rat (also known as the European water vole; Figure 8.4.6b). He was struck by an observation: animals that existed in very similar environments might bear almost no resemblance to one another at all.

We now know that this is because the water rat and the platypus do not share a recent common ancestor. The finches of the Galápagos Islands are closely related to finches of South America, and so they look similar. The water rat and the platypus do share some similarities: they are both mammals, both furred, both excellent divers and swimmers, and both consume plants that grow in or near the water. However, unlike the finches of the Galápagos Islands and South America, the platypus and the water are very different in many ways. For example, the platypus is a **monotreme** (an egg-laying mammal), while the water rat is a **placental** (a mammal that carries its young in utero). This important biological difference indicates that the platypus and water rat have been separated by millions of years of evolution.

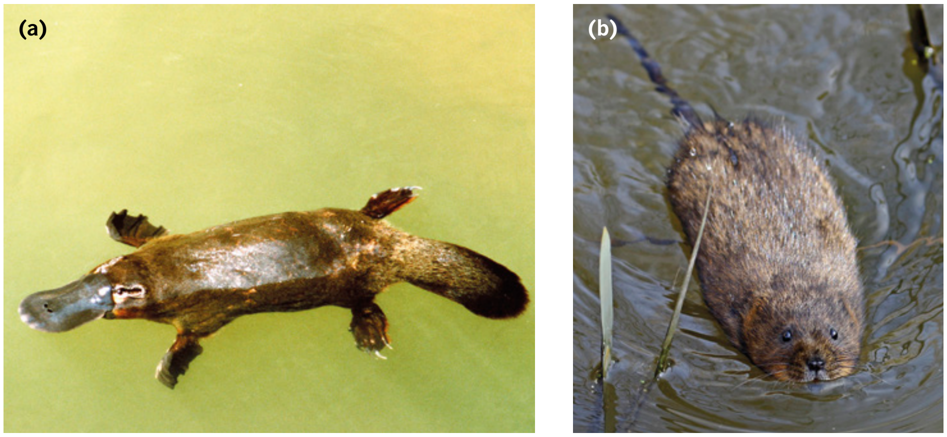


FIGURE 8.4.6 (a) The platypus (*Ornithorhynchus anatimus*) and (b) the water rat (*Arvicola amphibius*) occupy similar environmental niches, but—as Darwin noted—have very little physically in common, other than the fact that they are both aquatic mammals.

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Darwin's pigeons and unnatural selection

Finches were not the only birds that influenced the development of Darwin's ideas: he also bred pigeons.

The breeding of 'fancy pigeons' was a fashionable trend in Victorian England (Figure 8.4.5). Breeding pigeons allowed Darwin to explore how certain characteristics could be emphasised in the offspring of certain birds, and minimised in others. This process is apparent in all domesticated animals and plants, but seeing for himself how quickly pigeons could change over generations served as an excellent example of evolutionary change in action.

The most important difference between the breeding of domesticated animals and the evolutionary development of species is that the selection pressures are artificial, rather than natural. After *On the Origin of Species*, Darwin published another book on this topic called *The Variation of Animals and Plants Under Domestication* (1868).

FIGURE 8.4.5 A 19th-century colour image of domestic fancy pigeon varieties. Darwin bred pigeons for many years and made numerous observations of how it was possible to breed for both physical and behavioural characteristics.

Looking over his notes, Darwin would later consider these two observations:

- animals from the same region could closely resemble one another, even if they existed in very different environments
- animals in distant regions could look very different, even if they existed in very similar environments.

These two observations are key to understanding the theory of evolution by natural selection.

+ ADDITIONAL

Different theories of adaptation over time

Several theories have been proposed to explain the existence of all life on Earth. Today, the most widely accepted explanation is the theory of evolution: that new forms or species of life have evolved over time. The modern theory of evolution is the result of the combined works of Jean Baptiste Lamarck, Charles Darwin, Alfred Russel Wallace and Gregor Johann Mendel, beginning in the 18th century.

Jean Baptiste Lamarck (1744–1829)

Lamarck was a French naturalist and the first scientist to publish a reasoned theory of evolution. In France, he is regarded as the 'father of evolution' (Figure 8.4.7). He developed the theory of inheritance of acquired characteristics as a mechanism to explain how organisms changed over time. Lamarck argued that a particular trait was enhanced or diminished within the lifetime of an individual, depending on its use. The modified trait was inherited by offspring.

According to this theory, if, for example, a short-necked giraffe had to stretch to reach leaves, its neck would become longer over its lifetime. The offspring would have slightly longer necks as a result. In this way, giraffes' necks would continue to stretch until they reached their modern-day length.

Lamarck was developing his theory before the understanding of genetics. His theory was flawed, because it did not explain some situations, such as why the offspring of an amputee were born with all their limbs.

FIGURE 8.4.7 Bronze statue of Jean Baptiste Lamarck at the Jardin des Plantes (Garden of Plants), French National Museum of Natural History, Paris. The statue was constructed in 1909 to acknowledge Lamarck's contribution to evolutionary theory.

Alfred Russel Wallace (1823–1913)

Wallace was an Englishman who travelled extensively. He collected specimens in the Amazon and the region of Indo-Malaya (Figure 8.4.8). While travelling, he independently came up with the same idea of evolution by natural selection as Darwin (which spurred Darwin on to publish his work, *On the Origin of Species*).

FIGURE 8.4.8 Butterflies collected by Alfred Russel Wallace during his expeditions throughout South America and the Malay Archipelago. The Wallace Collection contains more than 850 insect specimens and is kept at the Natural History Museum, London.

Gregor Mendel (1822–1884)

Mendel was an Austrian monk who studied agriculture and botany. In his garden, he experimented comprehensively with the inheritance of traits in pea plants (Figure 8.4.9). His findings became the basis of modern genetics and he is often referred to as the 'father of modern genetics'. However, he only became famous after his work on plant genetics was rediscovered in 1900: almost 20 years after his death.

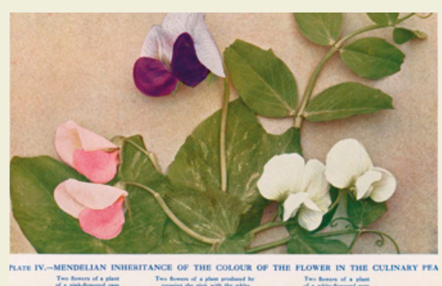

FIGURE 8.4.9 Gregor Mendel's breeding experiments with pea plants led to our understanding of the inheritance of traits. Mendel's work was so important that he is now often referred to as the 'father of modern genetics'.

THE MODERN MODEL OF NATURAL SELECTION

The model of natural selection that we use now has been refined and altered a great deal since Darwin's initial publication. While he proposed a mechanism of natural selection that drove species to adapt to their environment and separate from one another over time, he could not explain how characteristics were inherited across generations. Genetics did not yet exist as a field of study, and Mendel's influential work on peas would not be discovered until nearly 20 years after both Darwin and Mendel had died. We have now added our understanding of genetics and heredity into Darwin's original model, and we therefore have a much more detailed understanding of how natural selection works. In this context, natural selection and its role in the evolution of life will be examined in more detail in Chapter 9.

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Selection pressures and genetic variation

There is always variation between individuals within a population. **Genes** come in different forms. We use the term **allele** (gene variants) to describe these different forms. For example, a gene that affects hair could exist as an allele that produces curly hair, or an allele that produces straight hair. The various combinations of alleles in an individual make up their **genotype** (also known as an individual's genetics or genome).

The genotype, together with the environment, determine an individual's observable traits. These are also known as their **phenotype** (an individual's physical characteristics). For example, curly hair is a phenotype, while the combination of alleles that determine curly hair is a genotype. Another example is coat colour in dogs. Different combinations of alleles result in different coat colours (i.e. phenotypes) (Figure 8.4.10).

The total **genetic variation** in a population—that is, all the alleles that exist in that population—is referred to as the **gene pool**. The variation in the gene pool can also arise from random mate selection, recombination during gamete formation, the independent assortment of alleles during cell division, and random mutations. These factors, and the individual differences in gene expression and environmental factors, can lead to differences in phenotypes.

Genes are sections of DNA that code for specific traits in an organism. Genes are passed from parents to offspring. For example, pea plants have a gene for flower colour and a gene for seed colour.

A genotype is the combination of alleles in an organism. Genotypes determine the phenotype (physical characteristics of an organism).

The term 'gene pool' refers to all of the genetic variation (alleles) in a population.

FIGURE 8.4.10 Coat colour phenotype in dogs is determined by different combinations of alleles (genotypes). The number of black or brown dogs of a particular breed will depend on the frequencies of alleles in the population (the gene pool).

Alleles are different forms of a gene. For example, a gene for flower colour might have an allele for white flowers, an allele for pink flowers and an allele for purple flowers.

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FIGURE 8.4.11 Drought can create competition for resources such as water and food. This selection pressure can trigger changes in allele frequencies in a population.

Should a particular phenotype give an individual a survival advantage, that phenotype, and the genes and alleles that control it, is more likely to survive in the population. Successful organisms are more likely to breed, and those phenotypes will be inherited by their offspring, which in turn will be more successful than those with less useful phenotypes. For example, thicker-furred animals might be more successful at surviving and breeding in cold environments. Animals with thinner fur might be more tired and weak from cold, and therefore will be less able to survive, mate and rear young. Their offspring are also likely to inherit their less successful phenotypes and face many of the same problems.

The conditions or factors that influence which phenotypes are most successful in a population—and therefore, influence **allele frequency** in that population—are known as selection pressures. Selection pressures, together with mutation, are the driving force of evolution. Selection pressures can be natural environmental pressures or artificial pressures brought about by humans through selective breeding. You will learn more about artificial selection in Chapter 9.

Natural selection

Natural selection is the influence of environmental pressures on allele frequency in a population. Environmental selection pressures affect the survival and reproduction of an organism. Individuals with the most advantageous phenotypes have an increased chance of producing **viable offspring**. Viable offspring are offspring that are fertile and able to survive and breed the next generation.

Examples of environmental selection pressures include:

- climatic conditions, such as extreme temperature changes and drought (Figure 8.4.11)
- competition for resources, such as
  - food
  - water
  - shelter
- mate availability
- predator abundance.

The allele frequencies of a gene pool are heavily influenced by environmental pressures. This is because of the following factors.

- Variation—there are genetic differences between individuals of a population.
- Reproduction—organisms can reproduce and alleles are heritable. The offspring are genetically similar to parents (if sexually reproducing) or genetically identical (if asexually reproducing).
- Survival—not all individuals survive long enough to reproduce and produce offspring.
- Environmental selection pressures—some phenotypes are better suited to the environmental conditions and give the individual a survival and reproductive advantage over those of a different phenotype.

When it comes to survival, some phenotypes (traits) have a high **adaptive value** and give the individual an advantage over individuals with phenotypes of lower adaptive value. This concept is often referred to as 'the survival of the fittest'. Having an advantageous trait means the individual is more likely to survive to reproduce and pass their alleles on to the next generation.

Alleles for the advantageous trait tend to increase in frequency in the gene pool, while alleles of the less advantageous trait tend to decrease. Advantageous traits of high adaptive value may persist in the population until all individuals have the alleles for this trait (100% allele frequency). Over time, the population evolves and adapts to its environment.

Thorny devils (Figure 8.4.12), for example, have physical adaptations that enable them to thrive in the very arid ecosystems of central Australia. Their mottled camouflage colouring and hard spikes have high adaptive value, because these features reduce the likelihood of predation. Thorny devils also have highly textured skin, which allows capillary action to collect any moisture in their environment and channel it directly into their mouths.

The term 'allele frequency' describes the proportion of the gene pool that carries that allele, relative to other alleles for that gene.

FIGURE 8.4.12 The key physical characteristics of the thorny devil (*Moloch horridus*) are a result of increasing frequencies of alleles (gene variants) that provide phenotypes (physical traits) with high adaptive value.

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The antechinus

It is important to remember that natural selection acts to ensure the success of reproduction, rather than the success of the individual organism. This results in some rather puzzling behaviours.

A small Australian marsupial called an antechinus is an example of this phenomenon. (Figure 8.4.13). There are 15 species of antechinus, 14 of which exhibit extremely competitive breeding behaviour. Breeding occurs in winter, when few food resources are available. The male antechinus suppresses its immune system and sacrifices important protein to sustain a highly energetic, active and violent mating process. Once mating is over, males are physiologically exhausted and their survival rate is extremely low. Therefore, they usually breed only once in their lifetime.

This would seem to be a contradiction: how could such destructive behaviour be adaptive? The reason is that only very competitive males can breed successfully. Males that do not engage in this destructive behaviour do not breed, and so their genes are not passed on. Therefore, selection actually favours the competitive behaviour that kills the male antechinus.

FIGURE 8.4.13 The dusky antechinus (*Antechinus swainsonii*), like most antechinus species, has an extremely violent competitive mating system that results in the death of the male after breeding. This one is biting a researcher.

8.4 Review

SUMMARY

- Darwin's theory of evolution by natural selection was heavily influenced by his observations on the voyage of the HMS *Beagle*.
- Each island of the Galápagos Archipelago has a different environment. The finches of the Galápagos Islands were all similar species that had adapted to the specific requirements of their home island.
  - Darwin's observations showed that a single common ancestor could diverge into multiple distinct species in different environments.
  - The Galápagos finches are an example of adaptive radiation.
- Darwin visited Australia in 1836, where he observed that the platypus occupied the same sort of environment as the European water vole, but did not have many physical characteristics in common with the vole.
  - Darwin's observation showed that similar environments could support very different organisms.
  - We now know that the platypus and the water vole do not share a recent common ancestor.
- The modern model of natural selection incorporates our current understanding of genetics and is greatly refined from Darwin's original theory.
- Alleles are variants of a gene. One gene can have many different alleles (variants). An example is hair colour. Different combinations of alleles can determine different hair colours.
  - The phenotype is the physical characteristics of an organism.
  - The genotype is the combination of alleles in an individual.
  - The gene pool is the combination of alleles in a population.
- Natural selection is the influence of environmental pressures on allele frequencies of a population, which occurs because of genetic variation between individuals, and the survival and reproduction of those individuals with favourable phenotypes (traits):
  - Phenotypes that are better suited to environmental pressures have higher adaptive values than those that are less suited.
  - Individuals with alleles associated with the phenotype are more likely to survive and reproduce.
  - These alleles are more likely to persist in the gene pool and increase in frequency over time.

KEY QUESTIONS

1 Discuss the significance of the Galápagos finches to Darwin's theory of evolution by natural selection.

2 What is the major difference between Darwin's understanding of natural selection and the more refined model we use today?

3 How does the environment influence the frequency of different alleles in the population?

4 What is the difference between a phenotype and a genotype? Provide an example.

5 Write a brief definition of natural selection. What is meant by the phrase 'survival of the fittest'?

6 Provide three examples of environmental pressures that may influence natural selection.

7 New Zealand has no native land mammals other than three species of bat. Environmental niches that we would normally expect to be occupied by mammals are instead occupied by a diverse array of ground-dwelling birds, ranging from the kiwi to the enormous (and sadly extinct) moa. This is an example of:

A plate tectonics
B allele frequency
C selection pressure
D adaptive radiation.

Chapter review

08

KEY TERMS

abscission
adaptation
adaptive radiation
adaptive value
aestivation
allele
allele frequency
antifreeze protein
auxin
behavioural adaptation
bioluminescence
biomimicry
brumation
carotid rete system
chemotropism
common ancestor
countercurrent heat exchange
crassulacean acid metabolism (CAM photosynthesis)
deciduous
dehydrin
dentition
ecological niche
evaporative cooling
evolution
gene
gene pool
genetic variation
genotype
geotropism
gravitropism
halophyte
heat exchanger
hibernation
hormones
hydrotropism
innate behaviour
lenticel
malic acid
migration
monotreme
nastic movement
natural selection
organism
phenotype
photonasty
phototropism
physiological adaptation
placental
salinity
selection pressure
stimulus
structural adaptation
thermonasty
thermoregulation
thigmonasty
thigmotropism
tolerance range
torpor
trait
tropism
turgor
vascular
vasoconstriction
vasodilation
viable offspring
viviparous
xerophyte

REVIEW QUESTIONS

1 What are adaptations? Describe how they benefit individuals, populations and species.

2 Complete the following table, where S = structural, P = physiological and B = behavioural (or plant movement) adaptation.

Organism	Feature	S, P or B	Benefits to organism
mangrove	pneumatophore		
honey possum	long, brush-like tongue		
kangaroo	sleeps in shade during the day		
echidna	goes into torpor		
saltbush	salt-secreting glands in leaves		

3 The ability of the male southern pygmy perch to change colour in the breeding season and establish a territory is best interpreted as a:

A structural adaptation
B behavioural adaptation
C physiological adaptation
D limiting factor in reproduction

4 For each of the following environmental challenges, provide one structural adaptation and one physiological adaptation that would help an animal survive.

Environment	Adaptation	
	Structural	Physiological
desert		
snow		
deep underwater		
long, cold winter		
intertidal zone		

5 For each of the following environmental challenges, provide one structural and one physiological adaptation that would help a plant survive.

Environment	Adaptation	
	Structural	Physiological
desert		
snow		
tropical rainforest		
intertidal zone		

6 From the moment of germination, the roots of a new plant grow down into the soil. This is an example of:

A positive geotropism
B negative geotropism
C positive phototropism
D negative phototropism

7 Describe a behavioural adaptation that would help an animal to survive in a:

a hot, dry climate
b cold, wet climate
c highly variable climate

8 Jack rabbits, which are often found in deserts, have disproportionately large ears that have a rich network of blood vessels close to the skin. Kangaroos have a special network of capillaries that lie near the surface of the skin on the inside of the forearms. On very hot days, kangaroos can often be seen licking their forearms. State the type of adaptation and how this common feature might help each animal regulate its temperature.

9 Describe how an emperor penguin is adapted to life in the harsh Antarctic climate, mentioning at least one structural, one physiological and one behavioural adaptation.

10 Describe how CAM (crassulacean acid metabolism) photosynthesis is a beneficial adaptation for plants living in the desert.

11 Describe three adaptive advantages of bioluminescence, providing one example of each. Bioluminescence is particularly common in the ocean, suggesting that it is an advantageous trait, but it is comparatively rare on land. Why would bioluminescence be more advantageous in the ocean than on the land?

12 Approximately 2000 species of cichlid fishes have evolved in three east African lakes. Each species is specialised to occupy a different ecological niche. The term for this phenomenon is:

A artificial selection
B natural radiation
C adaptive radiation
D natural selection

13 On which of the following does natural selection act directly?

A the genotype
B the entire gene pool
C the phenotype
D each allele

14 What is meant by the term ‘torpor’? What is the adaptive advantage of states of prolonged torpor (i.e. dormancy)?

15 Provide a brief definition for each of the following types of prolonged torpor, making sure you understand the difference between each. Give an example of an animal that undergoes each form of torpor, and explain why it is advantageous for that animal to do so.

a hibernation
b brumation
c aestivation

16 Darwin observed that the European water vole and the Australian platypus occupied the same ecological niche. For each of these animals, describe one structural, one physiological and one behavioural adaptation that allows them to survive and function in their environment. You may need to research this using the internet. Once you have done this, list one adaptation (physiological, structural or behavioural) that is different between the two species and one that is the same.

17 Natural selection relies on genetic variation in a population. If all members of a population were genetically identical, evolution could not proceed. Explain why this is the case.

18 Pandas are an unusual example of niche specialisation. Examine the photos of (a) the skull of a giant panda (*Ailuropoda melanoleuca*) and (b) the skull of a black bear (*Ursus americanus*), paying particular attention to the teeth. Most bears are omnivores, but the giant panda has evolved to eat bamboo, although they can eat other plants and even some meat. In the modern world, habitat destruction means that this has been a disastrous specialisation for the species. In fact, the giant panda has been described as an 'evolutionary dead end'.

Considering your answer to Question 17, and with reference to the dentition (teeth) shown in these images, explain why giant pandas would have difficulty reverting to a more diverse diet, in terms of both their current form and their future evolution. (Hint: start by listing differences in the teeth. Consider what factors must be present to allow natural selection to take place.)

19 The male peacock has evolved an extraordinary tail in spite of the disadvantages of such a structure. This is an example of sexual selection (a form of natural selection associated with reproduction). What sort of selection pressure would encourage the development of the male peacock's tail?

A extreme climate
B predator abundance
C mate competition
D resource competition

20 Pick an example of a migrating animal. Describe its migratory practice, listing the adaptive advantages for that animal. What would happen if an individual of that species was not able to migrate?

21 For each of the three following environments, draw a diagram of a plant with appropriate adaptations. Label appropriate structures on leaves and roots. Note probable physiological and movement adaptations.

a hot, arid
b cold, wet
c high salinity

22 Choose any animal that hasn't been covered in this chapter. Research a structural adaptation and explain its usefulness in surviving the native environment of that animal. Does this adaptation occur in any other animals? Do those other animals live in the same or a similar environment? If not, how would this feature apply to a different environment?

23 After completing the Biology Inquiry on page 340, reflect on the inquiry question: How do adaptations increase the organism's ability to survive? Explain how adaptations can influence the evolution of a species.

CHAPTER

09 Theory of evolution by natural selection

This chapter examines the theory of evolution by natural selection, using it to explain biological diversity and the changes it has undergone since life first appeared on Earth. By examining the patterns of biological change over geological time, divergent and convergent evolution can be explained in terms of evolution by natural selection.

You will examine how an accumulation of microevolutionary changes can drive gradual evolutionary change over time and lead to speciation, looking at the evolution of the horse and platypus as examples. Although evolution is often a gradual process, you will learn that biological changes can also occur rapidly. This is known as punctuated equilibrium and is usually observed in the fossil record alongside sudden changes in the environment.

Content

INQUIRY QUESTION

What is the relationship between evolution and biodiversity?

By the end of this chapter you will be able to:

- explain biological diversity in terms of the theory of evolution by natural selection by examining the changes in and diversification of life since it first appeared on Earth (ACSBL088)
- analyse how an accumulation of microevolutionary changes can drive evolutionary changes and speciation over time, for example: (ACSBL034, ACSBL093) CCT L
  - evolution of the horse
  - evolution of the platypus
- explain, using examples, how Darwin and Wallace's theory of evolution by natural selection accounts for:
  - convergent evolution
  - divergent evolution
- explain how punctuated equilibrium is different from the gradual process of natural selection

9.1 Evolution and biodiversity

BIOLOGY INQUIRY CCT WE

Bird evolution

What is the relationship between evolution and biodiversity?

COLLECT THIS...

- drawing implements
- paper
- tablet or computer to access the internet

DO THIS...

1 From memory, sketch your favourite bird species in profile, paying attention to the beak.
2 Label your drawing with the species name and common name of the bird. Refer to the internet if you need to.
3 Think about the diet that the bird's beak is specialised for. List the types of food that the bird might eat next to your drawing.
4 Working in groups, repeat steps 1–3 for five different bird species. You can refer to the internet for ideas.
5 As a group, list the foods that are readily available to birds living in or around cities. Number the foods from least available (1) to most available (e.g. 10 if 10 foods are listed).
6 Discard the birds that do not have any foods available in city environments.
7 Allow the remaining birds to reproduce proportional to the amount of food available (refer to the numbers next to the available foods). Birds that are specialised to feed on the least available food (food 1) produce one offspring. Birds that feed on the 5th most available food produce five offspring. For birds that can feed on more than one food type, add up the numbers next to their food types to determine the number of offspring.

RECORD THIS...

Describe the bird species and beak shapes that remain.

Present your explanation for what happened. Compare with other groups.

REFLECT ON THIS...

What is the relationship between evolution and biodiversity?

Which bird species were most successful (i.e. produced the most offspring)?

How might selection pressures in cities and urban environments affect bird evolution and biodiversity?

FIGURE 9.1.1 Portrait of Charles Darwin, aged around 31, 1840

FIGURE 9.1.2 Alfred Russel Wallace, English naturalist (undated photo)

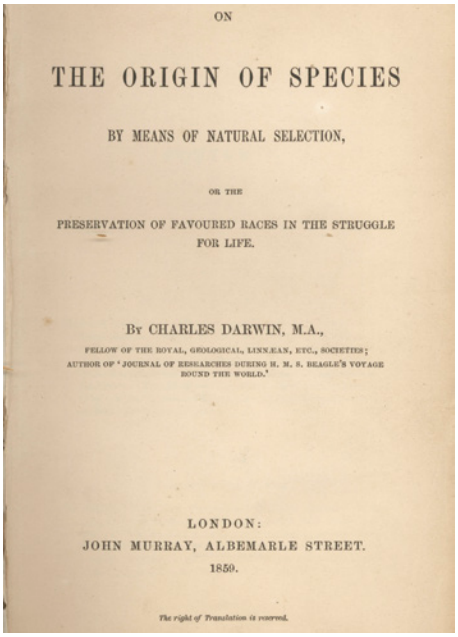
The phenotype is the physical expression of the genotype (the genes or alleles of an individual).

Evolution is the change in the genetic composition of populations over time. This can be observed as changes in **allele** frequencies (gene variants) and **phenotypes** (physical traits) in a population. New **species** can evolve in response to changes in environmental conditions or after populations become isolated and accumulate genetic differences. **Biodiversity** (the diversity of life) increases as genetic changes result in new **genetic variation** and the divergence of populations and species. In this sense, evolution promotes biodiversity. However, evolution can also lead to the loss of biodiversity, through the extinction of alleles, populations and species.

In Chapter 8 you learnt about the important contributions of Charles Darwin (Figure 9.1.1) and Alfred Russel Wallace (Figure 9.1.2) to our current understanding of evolution. In this section you will learn how their theory of evolution by **natural selection** accounts for different evolutionary processes and the diversity of life on Earth.

A MECHANISM FOR EVOLUTION: NATURAL SELECTION

In July 1858 two celebrated naturalists, Charles Darwin (Figure 9.1.1) and Alfred Russel Wallace (Figure 9.1.2), jointly presented a theory to the Linnean Society of London, which proposed a mechanism for species change. The two men had not worked together and had independently arrived at the same theory. The following year, Darwin published the theory in his book, *On the Origin of Species by Means of Natural Selection* (Figure 9.1.3).


ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

BY CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

The right of Translation is reserved.

FIGURE 9.1.3 Darwin's first edition of *On the Origin of Species by Means of Natural Selection*, published in 1859

The theory of evolution by natural selection proposed that species were not created in their present forms but had evolved from ancestral species. The work also proposed a mechanism for evolution, termed natural selection, based on two key observations.

1 Members of a population often vary in their inherited traits (Figure 9.1.4).

FIGURE 9.1.4 Harlequin ladybirds (*Harmonia axyridis*) vary in colour and the number of spots.

2 All species produce more offspring than their environment can support, and most of these offspring fail to survive and reproduce (Figure 9.1.5).

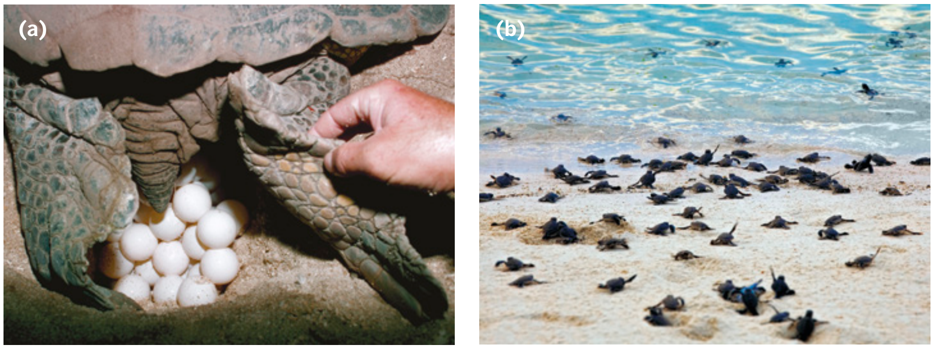


FIGURE 9.1.5 (a) The green turtle (*Chelonia mydas*) lays between 100 and 200 eggs in a single clutch, and in each season she may lay up to eight clutches. However, not all the eggs will hatch, and most hatchlings do not survive to adulthood. (b) Sea turtle hatchlings head towards the sea.

The environment acts on the phenotype (physical traits) of individuals.

Fitness in an evolutionary context means suitability for a particular environment.

FIGURE 9.1.6 The addax (*Addax nasomaculatus*) is extremely well-adapted to its desert environment. It can go without drinking water for its entire life, getting all the water it needs from the plants it eats. Its desert-adapted characteristics are a result of the selection of phenotypes (physical traits) with high adaptive value in a desert environment. The alleles for those phenotypes are then passed on to the next generation, increasing in frequency in the population.

Based on these two key observations, Darwin and Wallace drew two inferences.

1 Individuals whose inherited traits give them a higher probability of surviving and reproducing in a given environment tend to leave more offspring than other individuals.
2 This unequal ability of individuals to survive and reproduce will lead to the accumulation of favourable traits in the population over generations.

The theory of evolution by natural selection, also called Darwinian theory or **Darwinism**, is relatively simple to express, yet the processes it seeks to explain are complex.

At the time of the theory's publication, both Darwin and Wallace were unaware of the genetic basis of heritable traits and the mechanisms of **heredity**. Now we know what they did not: that the physical form (phenotype) of an organism is an expression of its underlying genetic information (**genotype**).

Individuals with the most advantageous phenotypes (traits) have an increased chance of producing fertile offspring. When it comes to survival, some phenotypes have a high **adaptive value** and give the individual an advantage over individuals with phenotypes of lower adaptive value. This concept is often referred to as 'the survival of the fittest'. **Fitness** refers to an organism's suitability to its environment. Having an advantageous phenotype means the individual is more likely to survive to reproduce and pass their alleles on to the next generation.

Every species that exists today has experienced evolution by natural selection. This can be seen in the specialised adaptations that enable organisms to survive in their environment. The addax (*Addax nasomaculatus*) is an example of an animal that is extremely well-adapted to its desert environment. The addax that are best-suited to hot, dry conditions will survive and reproduce; that is, they will be selected (Figure 9.1.6). The environmental conditions select the phenotypes that are well-suited to those conditions, enabling organisms with those phenotypes to live and reproduce in that environment. Individuals with traits that are not suited to their environment are less likely to survive or reproduce, and so are removed from the breeding population. What remains are the individuals that are suited to that environment.

Over successive generations, a greater proportion of the population expresses the well-suited traits (adaptive phenotypes) and a small evolutionary step has taken place.

Natural selection and adaptations are covered in detail in Chapter 8.

GO TO ➤ Section 8.4 page 373

Natural selection in action

Looking at changes in biological diversity, there are many examples that demonstrate the mechanisms of Darwin and Wallace's theory of evolution by natural selection. Further evidence and examples will be covered in Chapter 10.

GO TO ➤ Section 10.1 page 438

Insecticide resistance

Often when farmers start using a chemical insecticide to protect their crops, most of the insects have no defence and die. Yet a few are naturally resistant; the chemical does not kill them. The resistant individuals breed and pass on their resistant traits to some individuals in the next generation. Sexual reproduction results in parental genes being recombined in the offspring in new sequences; therefore, two surviving, resistant parents can still produce non-resistant offspring. The resistant individuals in the next generation again survive the insecticide, and go on to breed as well. In each subsequent generation vulnerable individuals die while those fit for the environment survive. With each generation the proportion of the insect population carrying the resistant trait increases, eventually approaching 100%.

The development of genetic resistance over many generations has been documented in numerous species. For example, DDT insecticide resistance in malaria-carrying mosquitoes, antibiotic resistance in many disease-causing bacteria and resistance to the disease myxomatosis in Australian rabbits. While not always about insecticides, these are similar examples of natural selection at work.

BIOFILE S

Myxomatosis in Australia

Members of Britain's colonising First Fleet brought rabbits to Australia in 1788, initially as food. The original population soon adapted to their new environment due to natural selection (Figure 9.1.7). After inevitable escapes following the switch to breeding rabbits in warrens rather than cages, combined with several intentional releases in the 1850s, rabbits rapidly became an invasive species (Figure 9.1.7). They stripped native vegetation, while also lowering agricultural productivity through soil erosion and competition with livestock.


FIGURE 9.1.7 (a) European rabbit in Tasmania (b) Rabbit plague in Australia, 1902

Control measures had no real effect, and by the 1950s Australia had around 600 million unwelcome rabbits. Australian scientists introduced the naturally occurring myxoma virus from Europe, which is deadly to rabbits. (The scientists also bravely demonstrated the virus' harmlessness to humans by testing it on themselves.)

The virus killed 99.5% of rabbits. Yet a resistant few survived and continued breeding. By 1991, the resistant individuals had bred up a new, myxoma-resistant population of over 200 million.

Lactose tolerance

Several thousand years ago, humans began domesticating cattle. Previously, the hunted wild animals had been a source of meat only, but domestication also made milk readily available. At first, a very high proportion of the human population was lactose intolerant, and unable to digest that component of the nutritious new food. Yet the fortunate few who could prospered, reproducing more successfully than the lactose-intolerant proportion. The frequencies of the alleles for lactose tolerance increased in the population. Today, lactose intolerance is rare in populations that have dairy in their diet, whereas populations that have little to no dairy in their diet have high levels of lactose intolerance. Populations in East Asia, Central Asia, Africa and southern India are examples of populations in which over 70% of people are lactose intolerant.

In all cases alleles of the advantageous trait tend to be more frequent in the gene pool, while alleles of the less advantageous trait tend to decrease. Advantageous traits of high adaptive value may persist in the population until all individuals possess them. Over time, the population evolves in response to environmental changes. This point is a key difference from **Lamarckism** (the theory of Jean Baptiste Lamarck), which proposed that the individual evolves.

Darwin noted the similarity of natural selection to **artificial selection**. The difference is that in artificial selection, human breeders take natural species and select traits they want retained in the next generation. These may include above-average milk or egg production, tameness in animals or sweetness in fruits. This can produce a new population substantially different from the original over a short period of time.

In contrast, natural selection does not operate by human design, and species usually change according to ecological factors. Such factors may include climate, competition for resources, predation or many others. Yet the potential for physical and other change in species due to natural selection is immense. This process has been responsible for nearly all change to life on Earth.

> The individuals that are best suited to the environment will be most successful; that is, they will survive and reproduce the most offspring.

> Individuals that reproduce pass their alleles on to their offspring.

Summary of natural selection

Natural selection is one of the mechanisms of evolution. The concept of natural selection is quite simple—individuals with traits that are well-suited to their environment survive and reproduce—but the way it functions in nature can be complex. The following points summarise the process of natural selection:

- Natural selection does not involve intent. Organisms never plan their eventual outcome, not even the most sophisticated camouflage or **mimicry**. Natural selection merely rewards whatever has already survived with ongoing survival: it does not estimate the likely chance of survival in the future.
- Consequently, selection does not work for the survival of the species. The mechanism favours individual survival and reproduction.
- Natural selection does not always lead to greater complexity or sophistication. Sometimes selection can lead to simplification, as in the loss of useless eyes in cave-dwelling or deep sea animals.
- Darwinian fitness does not mean athletic fitness. Fitness in an evolutionary context means suitability for a particular environment.
- Genetic variation not affecting the phenotype is selectively invisible and may accumulate over time.
- Not all traits serve a survival function. For example, human earlobes seem to have no purpose. Some traits are simply effects of developmental processes or other characteristics.
- Natural selection does not produce perfection. Most often, selection favours 'good enough' solutions that may be inelegant or inefficient.
- The evolution of complex structures such as eyes always proceeds in stages, each providing some advantage (Figure 9.1.8).

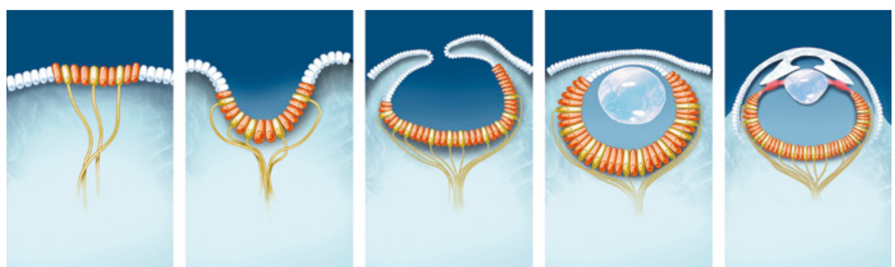


FIGURE 9.1.8 Step-by step evolution of an eye, each stage offering an incremental advantage to the animal. The stages include a patch of light-sensitive cells (left), followed by those forming a small depression, then a deeper depression, then a protective covering and finally a lens over the front.

BIOFILE CCT

Darwin in Australia

Charles Darwin was a self-financed passenger aboard HMS *Beagle* (Figure 9.1.9) during its second survey voyage around the world. His role was consultant geologist and naturalist.

The voyage lasted from 1831 to 1836. After leaving England, the ship visited Brazil, Argentina, Chile and Peru. In 1835 the vessel made its most famous stop, at the Galápagos Islands off the Pacific coast of Ecuador, for about one month. The HMS *Beagle* next visited Tahiti and New Zealand, then arrived in Sydney in January 1836.

The 27-year-old naturalist had not yet developed his famous theory, although he was aware of Australia's unique wildlife. Yet he also noted that other Australian species, specifically magpies and crows, were almost identical to their European counterparts. The same was true for the lion-ant, which Darwin identified as being of a different species yet the same genus of those he knew.

On the way home to England (via Mauritius), Darwin's experiences in Australia made him ponder the mixture of difference and similarity he had seen. He spent the rest of his life investigating the reasons.

FIGURE 9.1.9 HMS *Beagle* off the coast of South America. The ship took Charles Darwin on the voyage that inspired his theory of evolution by natural selection.

+ ADDITIONAL

Alfred Russel Wallace

Alfred Russel Wallace was born in Monmouthshire, England (now Wales) in 1823. The financial difficulties of his large family forced him to leave school at 14. He ended up roaming the English and Welsh countryside as a land surveyor, working for his elder brother. Wallace's desire to identify the flora he found while surveying sparked an interest in natural history. He educated himself about natural history and specimen collection and storage.

In 1843 the surveying business experienced hard times. Wallace gained employment as a teacher, and devoured the school library's natural history collection. The books convinced him that species do evolve.

In April 1848 Wallace, aged 25, left for Brazil with a friend from the school. The pair had intended to collect specimens, partly to sell and partly to find evidence for evolution. After parting company, Wallace continued sampling from the Middle Amazon and Rio Negro regions. He also drafted a detailed and highly regarded map of the area.

In 1852 Wallace set sail for home due to illness. On the way, the ship caught fire and sank, along with two years' worth of Wallace's specimens and irreplaceable notes. The survivors were rescued after 10 days adrift in lifeboats.

Two years later Wallace left for what was then called the Malay Archipelago (now Malaysia and Indonesia) (Figure 9.1.10). There he spent the next eight years collecting over 100 000 specimens, including 5000 species new to science (Figure 9.1.11). His 1855 paper 'On the Law which has Regulated the Introduction of New Species', published in *Annals and Magazine of Natural History*, detailed preliminary ideas on speciation. Speciation is examined in more detail in Section 9.2.

Wallace's work prompted prominent geologist, Charles Lyell, to discuss the paper and species change with Charles Darwin. At the meeting, Darwin outlined his own ideas about evolution for the first time. Lyell urged Darwin to publish soon in case Wallace beat him to it.

Wallace, living on the island of Halmahera, fell ill with fever in 1858. During his recovery, the principle of evolution by natural selection became clear to him through sudden insight. This was in contrast to Darwin's more painstaking and deductive approach over many years. Wallace wrote the theory as an essay and sent it to Darwin, with whom he had corresponded, asking that Darwin pass it on to Lyell.

Without Wallace's permission, Lyell and other members of the Linnean Society decided to simultaneously present Wallace's essay and excerpts from Darwin's writings to the Society. Wallace later agreed that Darwin should have priority on the theory.

Wallace remained in the archipelago for a further four years. He became known as the greatest authority on the biogeography of the region. You will learn more about Wallace and his contribution to biogeography in Chapter 10.

In 1862, 39-year-old Wallace returned to England. He spent the rest of his life popularising evolution and writing prolifically about various scientific and social subjects. He received a string of prestigious awards, including the Order of Merit which is the highest honour available to a British civilian. He died in 1913, aged 90.

FIGURE 9.1.10 Malay house in the Aru Islands, Indonesia. Alfred Russel Wallace lived in many similar dwellings during his travels.

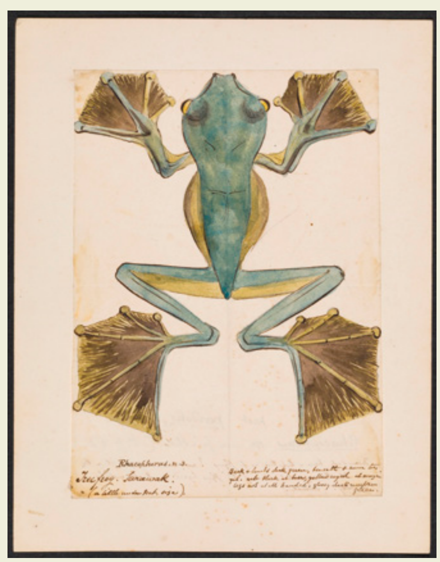


FIGURE 9.1.11 A drawing by Alfred Russel Wallace of a tree frog from Sarawak, Malaysia

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PUNCTUATED EQUILIBRIUM

Natural selection is commonly misunderstood to mean constant, directional change.

Darwin was also guilty of this mistake; he predicted that the evolution of species occurs gradually and that the **fossil record** would reflect this, with transitional forms of species as they underwent evolution from one form to another. Although such forms do exist in the fossil record, more than 70% of fossil sequences show relatively rapid change, rather than gradual change. Evidence of gradual evolution in the fossil record is comparatively rare, implying that most evolution must be rapid.

A modification to Darwinism, called **punctuated equilibrium**, explains rapid evolutionary change.

The theory of punctuated equilibrium predicts that over geological time, the main selection pressure on a species will be for stability. Once an organism is well-adapted to its environment, selection acts to maintain the well-adapted traits. The fossil record for that species would then show long periods of no change (the equilibrium).

Yet such periods are punctuated with short bursts of very rapid change to a new stable form. When evolution does occur, it is still gradual, but occurs so rapidly that the transitional forms are seldom preserved in the fossil record. Hence the fossil record mostly shows sudden jumps; these sudden changes punctuate the equilibrium.

Sudden changes in the environment cause rapid evolutionary change. A species well-adapted to the previous environment is vulnerable during environmental change and so is under intense selection pressure to evolve and adapt as rapidly as possible. This rapid evolutionary change has been seen in the cane toad since its arrival in Australia just over 80 years ago.

TYPES OF EVOLUTION

Coevolution

Species that interact closely exert selection pressures on each other. Both species also experience similar environmental conditions. In such situations **coevolution** can be seen, with the two species evolving together in a reciprocal response to selection pressures.

Coevolution is often seen in flowers and their pollinators. New variations of flowers appear through mutation, and these may be more likely to survive and produce seeds. As a result, some pollinators will be more suited to these flowers, and will therefore evolve alongside the flowers (Figure 9.1.12). Coevolution can also be observed in predator–prey relationships. When predators pick off the weaker prey, stronger individuals are left to reproduce. The next generation of predators will need to be stronger and faster to keep up with the stronger prey.

FIGURE 9.1.12 *Lonicera gracilipes*, an early spring flower, produces nectar collected almost exclusively by andrenid bees (*Andrena lonicerae*). This is achieved by the long narrow corolla tube of the flower, which allows the long tongue of the andrenid bees to reach the nectar but prevents pollinators with a short tongue from doing so.

Parallel evolution

Parallel evolution is the evolution of similar features in related species that have experienced similar environments and selection pressures. For example, the similarities in the colouration of different bird species that live in similar environments.

Convergent evolution

Convergent evolution is the evolution through natural selection of similar features in unrelated groups of organisms (Figure 9.1.13). Unrelated species that have adapted to a particular environment in similar ways are said to have converged, or become more alike.

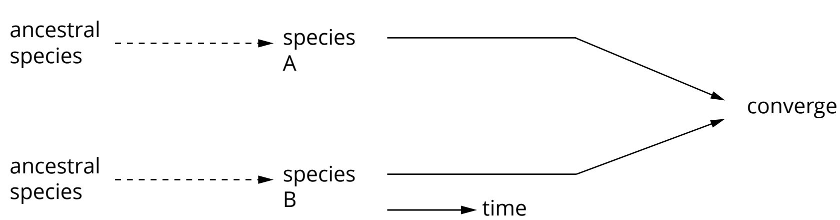

FIGURE 9.1.13 Convergent evolution

The Australian **marsupial** sugar glider (*Petaurus breviceps*) and the American **placental** flying squirrel (*Glaucomys* sp.) have both developed large membranes between their fore and hind limbs that enable them to glide successfully (Figure 9.1.14). This is an example of two unrelated species that have converged due to similar environments and lifestyles despite different origins.

FIGURE 9.1.14 (a) The Australian marsupial sugar glider (*Petaurus breviceps*) and (b) the American flying squirrel (*Glaucomys* sp.) have many features in common, although they are not closely related. They are an example of convergent evolution.

In general, similar selection pressures tend to produce a strong resemblance among unrelated species.

The process of convergent evolution can also produce similar-looking features from entirely different ancestral structures. For example, cephalopod (the order containing octopus and squid) and vertebrate eyes outwardly look similar (9.1.15). Yet the similarity is superficial; examination of the differences shows that natural selection has produced the same result using different tissues and in a different arrangement. Relative to the lens, vertebrate eyes have the nerve fibres in front of (i.e. over the top of) the light-sensitive retina, while the nerve fibres in the cephalopod eye are behind the retina (Figure 9.1.15). In vertebrate eyes, the nerve has to pass through the retina on the way to the brain, resulting in an inefficient blind spot. Cephalopod eyes lack this limitation.

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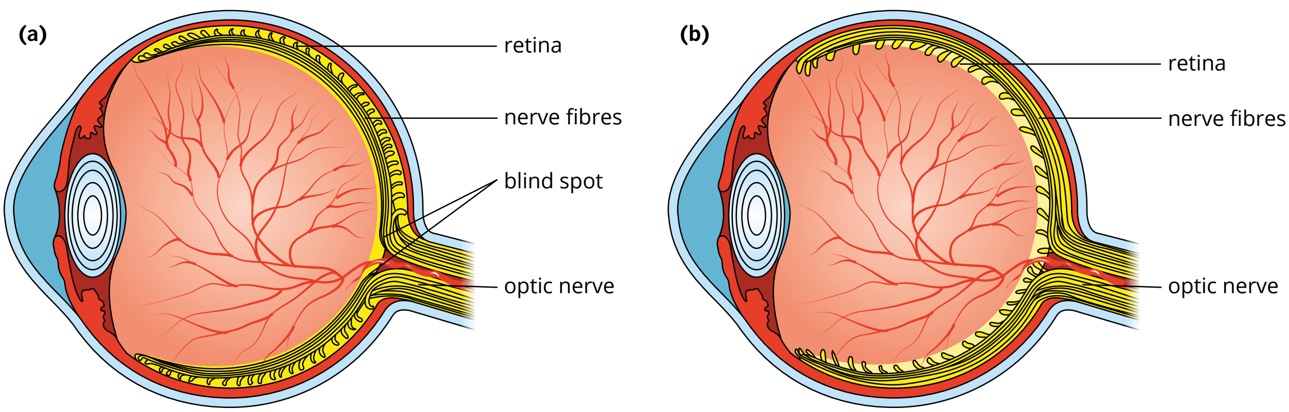

FIGURE 9.1.15 (a) Vertebrate eye and (b) cephalopod eye

BIOFILE CCT

Convergent evolution: Ichthyosaurs and dolphins

Generally, similar selection pressures produce similar adaptations, even in unrelated species.

For instance, the extinct ichthyosaurs looked very much like modern dolphins (Figure 9.1.16). Both families had the same habitat (open ocean) and the same diet (schooling fish). Although the origins of these groups were separated by more than 200 million years, natural selection faced the same problems and produced similar results in both cases.

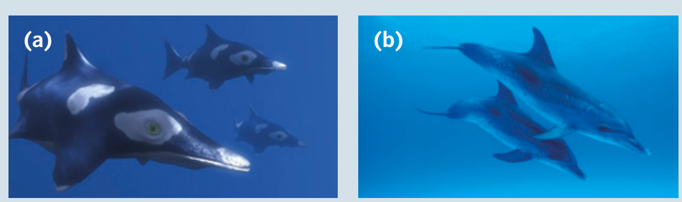

FIGURE 9.1.16 (a) Triassic reptilian Ichthyosaurs. (b) Two Atlantic spotted dolphins (*Stenella frontalis*). The comparison shows the similar body forms of unrelated species due to converging lifestyles and selection pressures.

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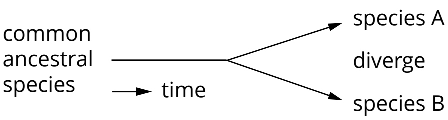


FIGURE 9.1.17 Divergent evolution

Divergent evolution

Separated populations typically diverge. Whether by random factors such as **genetic drift** (random changes in allele frequencies) or by natural selection, separated populations gradually become different (Figure 9.1.17). This is called **divergent evolution**. Genetic drift is examined in Section 9.2.

After enough difference has accumulated, the populations lose the ability to interbreed. Thus, one parent species can give rise to many new species in a process called **speciation**. Speciation is covered in more detail in Section 9.2.

Among the new species, selection pressure usually favours populations that can avoid resource competition and exploit new niches. An example of divergent evolution is the many finch species on the Galápagos Islands. They are believed to have diverged from a common South American ancestor and some specimens were collected by Darwin during his voyage on the HMS *Beagle*.

BIOLOGY IN ACTION CC S

Desert lizards

Dr Jane Melville is a research scientist at Museum Victoria, specialising in the evolution of lizards. She has done extensive fieldwork in desert environments, comparing species within and between different lizard families based on DNA and morphological and behavioural characteristics.

Divergent Australian species

In outback Australia, the bearded dragon (*Pogona vitticeps*) and the earless pebble dragon (*Tympanocryptis cephalus*) are two related species classified in the same family (Agamidae). However, they have diverged over time, look distinctive and behave quite differently (Figure 9.1.18a, b). The bearded dragon is a large animal with short limbs and spines. It is found over large areas of arid and semi-arid Australia, where it perches on tree limbs, stumps and fence posts. When threatened, it extends its spiny beard, opens its mouth and will make lunging movements towards its attacker. In contrast, the earless pebble dragon is a small animal with short limbs and tail. It is found in the stony deserts of Australia and is a stone mimic. When threatened, it freezes and crouches down so that its head and body resemble a stone and its tail a dry twig.

The Australian bearded dragon and the earless pebble dragon have different adaptations to living in Australian desert environments and are an example of divergent evolution.

Stone mimics on two continents

Dr Melville has also studied lizards in stony deserts in the south-west of the USA. The round-tailed horned lizard, *Phrynosoma modestum* (Figure 9.1.18c), looks remarkably like the Australian earless pebble dragon *Tympanocryptis cephalus* (family Agamidae) (Figure 9.1.18b), but it is in a different family (Iguanidae). The round-tailed horned lizard is also a stone mimic. When disturbed it freezes, closes its eyes and takes up a pose so that it resembles a small rock. Like the Australian earless pebble dragon, it will curve its back into a hump. Its dark side-markings resemble the shadows of a stone, and the tail banding makes the tail look like a dead twig.

Despite more than 100 million years of evolutionary separation and living on different continents, the Australian pebble dragon and American round-tailed horned lizard show significant convergent evolution in body shape and behaviour—adaptations that enable them to survive in hot, dry conditions and to live on stony desert plains.

FIGURE 9.1.18 (a) The Australian bearded dragon (*Pogona vitticeps,* family Agamidae), (b) the Australian earless pebble dragon (*Tympanocryptis cephalus*, family Agamidae) and (c) the American round-tailed horned lizard (*Phrynosoma modestum*, family Iguanidae). The Australian earless pebble dragon (b) and the American round-tailed horned lizard (c) are both stone mimics, with similar adaptations to living in stony deserts in different parts of the world.

+ ADDITIONAL

Artificial selection

Humans have been manipulating allele frequencies in the gene pools of populations for thousands of years through deliberate selection of particular individuals. The process humans use to decide which individuals may breed and leave offspring to the next generation is called artificial selection or selective breeding.

Artificial selection has led to improved agricultural crops and the domestication of animals for food or other uses. The animals and plants we use for food today are the result of many generations of artificial selection (Figures 9.1.19 and 9.1.20). Animals have also been artificially selected for companionship (e.g. pet dogs), sport and transport (e.g. horses). Darwin kept and bred pigeons, gathering information from stockbreeders. While developing his theory of evolution by natural selection, he observed the success of such artificial selection in producing new types of pigeons.

Through selective breeding, humans choose individual organisms with desirable traits and deliberately interbreed them to increase the **allele frequency** of those desired traits in the gene pool. This allows selected forms to reproduce while preventing undesirable forms from reproducing.

FIGURE 9.1.19 (a) Aurochs (*Bos primigenius*), the ancestors of (b) modern cattle (*Bos taurus* and *Bos indicus*), were almost twice the size of their domesticated descendants and very aggressive. Aurochs were a wild type of cattle found across Europe, North Africa and Asia and are now extinct.

FIGURE 9.1.20 Two different sizes of cultivated strawberries (centre and left) next to a wild strawberry (right).

Selective breeding in plants

Most selective breeding of plants is done to produce higher quality food. Typically, seeds are collected from the individuals with the largest or most numerous grains, fruits, nuts or other part of the plant that will be eaten. Those seeds are planted and the new generation of plants is cross-pollinated with other individuals with similar traits. The resulting plants produce larger, more nutritious or more aesthetically pleasing food products.

Maize, or corn (*Zea mays*), is one of the most widely grown crops in the world. It is thought that maize was selectively bred from a wild grass called teosinte (*Balsas teosinte*). Modern maize has significantly larger cobs with many more rows of much larger kernels compared to the ancestral teosinte. The higher yielding modern maize provides more food for people than the ancestral form (Figure 9.1.21).

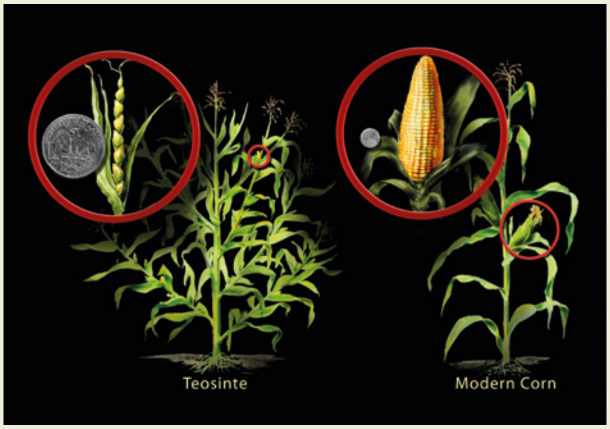


FIGURE 9.1.21 The ancestral species (*Balsas teosinte*) compared to cultivated corn (*Zea mays*). The modern plant has fewer side branches, which has resulted in fewer, but larger ears.

+ ADDITIONAL *continued*

Many other food crops, such as tomatoes, potatoes and grains, have also been modified by selective breeding to have higher yields, as well as greater resistance to common diseases.

Selective breeding in animals

Just as crops have been selectively bred for desired traits, so too have many animal species. In agriculture, sheep have been selected for the quality and quantity of the wool they grow, dairy cows have been selected for the milk they produce, and beef cattle for their muscle mass.

When a species has a variety of traits, different traits may be useful in different situations. A single wild species can be the original source of a great variety of different breeds. For example, it is widely accepted that all domestic dogs (*Canis familiaris*) were selectively bred from a now extinct grey wolf species (Figure 9.1.22). Today there are hundreds of domesticated dog breeds, some of which would be unlikely to survive in the wild. Examples include soft-mouthed, strong swimming dogs such as labradors, which were bred for duck hunting, and sheepdogs, bred for their intelligence. Humans have also artificially selected for a wide variety of traits in chickens, horses and many other domestic animals to produce gene pools that consistently produce the desired traits.

FIGURE 9.1.22 Dogs have been selectively bred for particular traits, such as size, coat colour, speed, protectiveness, strength or endurance.

9.1 Review

SUMMARY

- Charles Darwin and Alfred Russel Wallace developed a theory to explain the mechanism of species change and the evolution of biodiversity. This theory is known as the theory of evolution by natural selection.
- Natural variation exists between individuals of the same species because individuals are genetically different—many genes have multiple alleles (gene variants) that are present in the population in different frequencies.
- Allele frequencies are a measure of how common a particular allele is in the gene pool of a population.
- Different alleles have come about through mutations in DNA.
- The combination of genes or alleles in an individual is known as the genotype.
- The phenotype is the physical expression of the genotype (the genes or alleles of an individual).
- Evolution is change in the genetic composition of populations over time. Allele frequencies change in response to natural selection, depending on the adaptive value of the related phenotypes, or by genetic drift (changes by chance in small populations).
- Natural selection is the influence of environmental pressures on allele frequencies of a population.
- Natural selection occurs because of genetic variation between individuals, and the survival and reproduction of those individuals with favourable phenotypes (traits).
  - Phenotypes that are better suited to environmental pressures have higher adaptive values than those that are less suited.
  - Individuals with alleles associated with the adaptive phenotype are more likely to survive and reproduce.
  - These alleles are more likely to persist in the gene pool and increase in frequency over time.
- Natural selection usually operates gradually, but in most cases the gradualness is not apparent in the fossil record.
- Species typically evolve rapidly when environmental conditions change until they reach a new stable fitness. This is why the fossil record normally shows long periods of no apparent change punctuated with brief evolutionary bursts. This is known as punctuated equilibrium.
- Three types of evolution by natural selection are:
  - coevolution, where two or more unrelated species that interact closely evolve in response to one another (e.g. flowers and pollinators or predators and prey)
  - convergent evolution, where similar environments and selection pressures drive unrelated species to resemble each other, or to produce similar structures independently
  - divergent evolution, where populations with a common ancestor become increasingly different over time (i.e. they diverge); divergent evolution usually occurs after populations have been separated and experience different environments and selection pressures.
- When species fail to adapt to changing selection pressures, extinction results.

KEY QUESTIONS

1 Define ‘natural selection’.

2 Briefly explain the theory of evolution by natural selection.

3 State three key factors that contribute to natural selection.

4 **a** What is punctuated equilibrium?
b How are fossil records different when referring to punctuated equilibrium?

5 Name three types of evolution by natural selection.

6 There is a striking similarity between the eye of a vertebrate, such as a shark, and that of an octopus.
a What is the evidence that these eyes did not evolve from a common ancestor?
b What is the likely reason for the evolution of a similar type of eye in octopuses and vertebrates?

9.2 Speciation and microevolutionary change

> Gene flow is the transfer of genes or alleles between populations.

The ability to **interbreed** defines species. Interrupting breeding and the exchange of alleles through isolation can lead to the evolution of new species.

Gene pools can change when new individuals join the population from a different gene pool or when some individuals leave a population. Such migration of individuals can result in **gene flow**.

When gene flow exists between two different populations, the gene pools may remain fairly similar. When gene flow is absent between populations, the gene pools are said to be isolated.

Different selection pressures and different mutations in the separated populations cause them to become genetically different. Eventually, the separated populations may accumulate different characteristics, become reproductively isolated and be recognised as two new species. The new species may be subject to different selection pressures and so the gap between them will widen; they will diverge.

Genetic isolation of one species from another can be a result of one or more mechanisms. In this section you will learn that these mechanisms can act before reproduction (prezygotic) or after reproduction (postzygotic).

BIOFILE L

Naming species

Each species has a scientific binomial (two-part name) classification—the first word is the **genus** and the second the species name. Genus starts with an uppercase letter and species with a lowercase letter. The genus and species name should always be written in italics. For example, *Agra sasquatch* and *Agra vation* are the scientific names for two different kinds of beetles. Both species belong to the same genus *Agra*.

The same convention is used internationally to aid scientific communication between all cultural and language groups. When an individual species name is unknown, the abbreviation *sp*. is used, or the plural form *spp*. for several species in the same genus.

SPECIES

A species is the largest group of individuals that can breed with one another. In order to be considered members of the same species, individuals must be genetically similar enough to produce fertile **viable offspring** (Figure 9.2.1). A species can also be thought of as a **gene pool** that is isolated from the gene pools of other species.

While this definition of species fits most groups of organisms, there are exceptions. For instance, organisms that reproduce asexually, particularly single-celled organisms, can be difficult to categorise into discrete species. Also, species covering a wide geographic range may vary subtly over that range. Adjacent populations may freely interbreed, but the two extreme ends of the range may be genetically incompatible.

The current definition of species is also problematic because of another important fact: species change.

Fossil evidence shows that many species existed in the past that do not now, and that the species we see today did not exist in the past. Thus, species come and go. Fossil evidence also shows that while species exist, they can take on different forms over time.

Around the end of the 18th century, it was accepted that species change (evolve). However, the scientific community did not know the mechanisms by which the changes occurred.

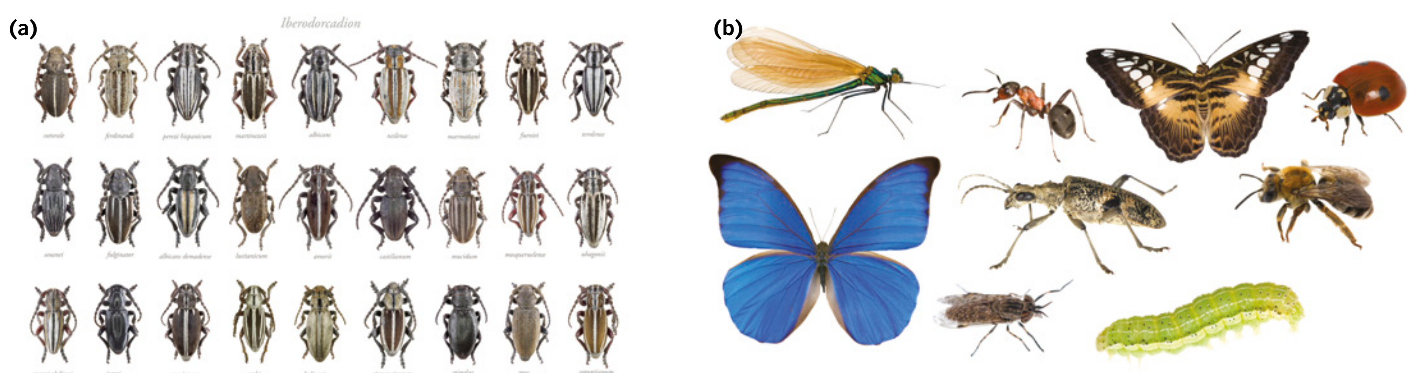


FIGURE 9.2.1 (a) Separate species of the longhorn beetle genus *Iberodorcadion*: each species is similar but subtly different, forming its own separate interbreeding population. (b) There are close to 1 million known insect species on Earth; the diversity is largely due to different selection pressures over a long period of time.

BIOFILE CCT

The species problem: Neanderthals and humans

The Neanderthal people were outwardly very human-like. Given a shave and a haircut, a hypothetical Neanderthal visitor to the modern world could have walked among us without drawing much attention.

Yet in spite of their similarities to us, Neanderthals also had significant differences. Our ancestors undoubtedly noted the Neanderthals' heavy brow ridges, large noses and flatter foreheads (Figure 9.2.2). Neanderthal dietary proportions were also reversed compared to *Homo sapiens* (our species), with 80% of their food being meat. This was not a cultural preference, nor a necessity of ice age hunting; Neanderthal digestive systems were very different to ours. The Neanderthals' strong musculature also limited shoulder movements: Neanderthals could neither swim nor throw. Contrary to some interpretations, Neanderthals did have the anatomy for speech, yet their voices would have sounded alien to humans. Another difference was that Neanderthals probably had superior eyesight to ours.

Such large physical differences clearly justify Neanderthals' classification as a different species: *Homo neanderthalensis*. Yet that is a problem for the definition of species, since some limited interbreeding between Neanderthals and humans did occur. There is DNA evidence, both from fossil Neanderthal and modern humans, that this interbreeding occurred in Europe and Asia after ancestors of modern humans migrated out of Africa. So our own species and nearest relatives are in fact examples of the imperfection of the modern definition of species.

(a)

(b)

FIGURE 9.2.2 (a) Model of a Neanderthal man (*Homo neanderthalensis*). (b) Neanderthals lived across Europe, the Middle East and Central Asia during the most recent ice age, from around 250 000 years ago to approximately 30 000 years ago.

Neanderthals were not ancestral to modern humans. Humans and Neanderthals shared a common ancestor that existed between 600 000 and 1 million years ago.

PREZYGOTIC ISOLATING MECHANISMS

Prezygotic isolating mechanisms are those that prevent individuals from different species from interbreeding (producing fertile offspring). Prezygotic isolating mechanisms may prevent individuals coming into contact, prevent mating when they do come into contact or prevent fertilisation if mating occurs. There are a variety of prezygotic isolating mechanisms that work to prevent interbreeding at different stages.

Geographical (spatial) isolation

Populations may be separated by physical and geographical barriers, such as oceans, deserts, mountain ranges and glaciers. For example, the southern boobook (*Ninox boobook*) is an Australian owl that is genetically distinct from the New Zealand owl, morepork (*Ninox novaeseelandiae*) (Figure 9.2.3). One reason that they are genetically isolated is that the Tasman Sea separates them.

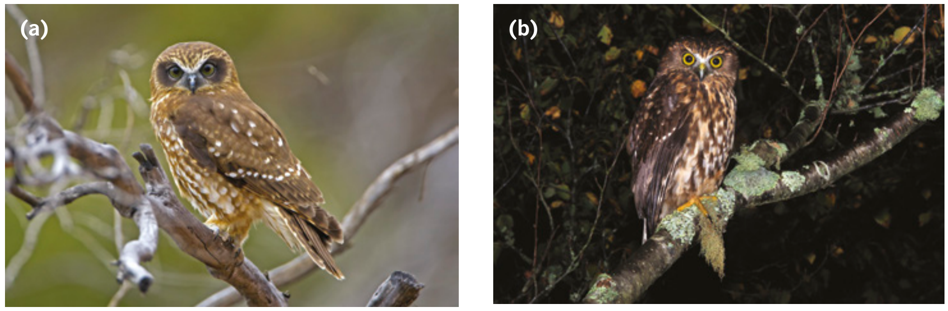


FIGURE 9.2.3 Australia's southern boobook (*Ninox boobook*) (a) is closely related to the New Zealand morepork (*Ninox novaeseelandiae*) (b). The two species are separated by a geographical barrier.

Ecological isolation

Populations occupy different **ecological niches** within the same ecosystem. For example, brown stringybark (*Eucalyptus baxteri*) and Mt Abrupt stringybark (*Eucalyptus verrucata*) are closely related species that grow side-by-side in the Grampians, in Victoria. Mt Abrupt stringybark grows on upper slopes on rocky sites and brown stringybark occurs on lower slopes on deeper soils. The two species are usually reproductively isolated but sometimes their flowering times overlap and neighbouring trees will interbreed. **Hybrids** (the offspring of two different species) are fertile, but are generally found only along the border between the two species. The obvious boundary between species can be seen in Figure 9.2.4.

FIGURE 9.2.4 Mt Abrupt stringybark (*Eucalyptus verrucata*) is a small, hardy shrub that grows on shallow soil and rocky sandstone slopes. Brown stringybark (*Eucalyptus baxteri*) occurs on deeper soils where the bedrock has weathered more. The sharp boundary between the two species can be seen at Mirranatwa Gap, in the southern Grampians. The boundary corresponds to a distinct change in the texture of the sandstone and soil depth.

Temporal isolation

The breeding cycles or active times of populations do not overlap. For example, a nocturnal animal is unlikely to breed with a diurnal one. Likewise, many similar plant species will flower at slightly different times of the year, preventing cross-pollination.

Behavioural isolation

This occurs when behaviours such as mating calls and courtship rituals are different. This isolating mechanism is only possible in animals. An example is mate attraction to different types of vocal signals, such as bird songs or frog calls, which are unique to species. Behavioural isolation is often the result of sexual selection (see page 397).

Structural or morphological isolation

The reproductive organs of different species are physically incompatible and individuals are unable to mate. For example, a sparrow could not breed with an albatross. For more similar species, even slight differences can prevent mating, such as the different breeding pheromones produced by different moth species.

Gamete mortality

This occurs after mating has taken place. Egg and sperm (**gametes**) fail to fuse in **fertilisation** and a **zygote** does not form. For example, the sperm of one species may not be able to recognise the egg of another without the appropriate signalling molecules, or the conditions of the female reproductive tract of one species may not sustain the sperm of another species. Pollen may not germinate on the style of the flower of another species due to a chemical barrier, preventing the plant's sperm from reaching an ovum.

POSTZYGOTIC ISOLATING MECHANISMS

Postzygotic isolating mechanisms are those that typically prevent a zygote of two different species from developing into a fertile adult. The offspring resulting from interbreeding between individuals from different species are called hybrids.

Hybrid inviability is a mechanism of **reproductive isolation** in which the sperm from one species successfully fertilises the egg of another species to form a hybrid zygote, but the hybrid zygote has unmatched chromosomes. As a result, normal embryonic development cannot proceed because of the lack of homologous chromosome pairs in the zygote. The zygote does not usually survive long.

Sometimes the zygote survives and undergoes cell division but the offspring does not develop fully and will not reach adulthood. This is known as reduced hybrid viability. Most hybrids that do develop into adulthood are sterile; that is, they are incapable of producing offspring themselves (Figure 9.2.5). Hybrid sterility usually results from problems during gamete formation. One of the best-known hybrids is the mule (Figure 9.2.22 on page 409). As the offspring of a female horse ($2n = 64$) and a male donkey ($2n = 62$), the mule has 63 chromosomes in total. Hybrids such as the mule do not have homologous pairs of chromosomes because their genetic material came from different species. Without homologous pairs, meiosis cannot proceed normally and the gametes, if any are formed at all, cannot interact correctly in order for fertilisation to occur. Mules, like all hybrid offspring, cannot reliably reproduce. Mules are still valued and used for some purposes today. Each breeding of a mule requires crossing a male horse and female donkey.

In some situations the first generation of hybrids is semifertile and can occasionally produce offspring when reproducing with another hybrid or with one of the parental species. However, the second generation is typically sterile. This form of postzygotic isolating mechanism is called hybrid breakdown.

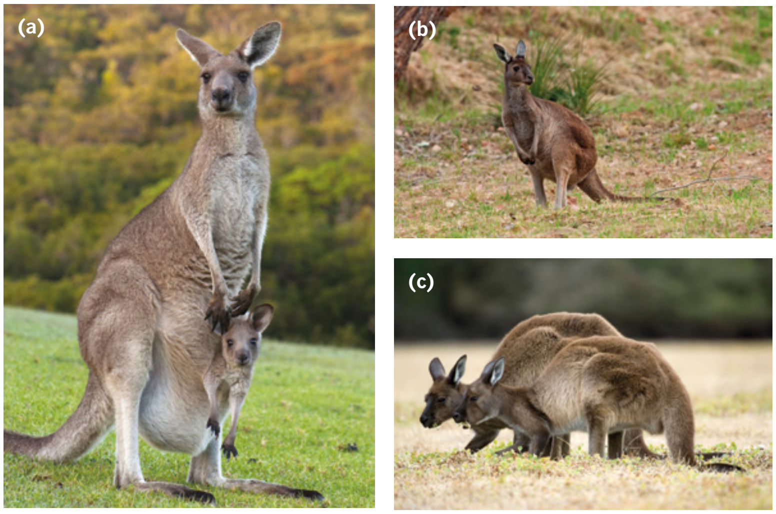


FIGURE 9.2.5 (a) Eastern grey kangaroos (*Macropus giganteus*) were crossed with a very similar but separate species, (b) the western grey kangaroo (*Macropus fuliginosus*). (c) The resulting male joeys were all sterile.

SEXUAL SELECTION

Sexual selection is a selection pressure that also functions as a prezygotic isolating mechanism.

Most animals exhibit some level of sexual selection in which at least one sex selects their mate based on specific traits. Although it may appear that mates are chosen on the basis of an irrelevant characteristic, the chosen traits are often indicators of good health, strength and fitness or high adaptive value. The alleles of these mates will then be inherited by offspring. Sexual selection is particularly common in birds. For example, barn swallows (*Hirundo rustica*) select mates based on the length of tail streamers (elongated tips of tail feathers), which indicate health and fitness.

BIOFILE N

Chromosome numbers

Body cells contain chromosomes in matching pairs (known as homologous pairs), so $2n$ refers to this diploid (paired) number. A gamete cell has half the number (n) of chromosomes, known as the haploid number—one from each pair. The letter code is used because species have different n and $2n$ numbers. In humans $2n = 46$ and $n = 23$.

BIOFILE CCT

Lions and tigers and ligers

A liger (Figure 9.2.6) is the hybrid offspring of a male lion (*Panthera leo*) and a female tiger (*Panthera tigris*). Both lions and tigers have two sets (diploid) of 38 chromosomes ($2n = 38$). Ligers also have a diploid number of 38 chromosomes. However, due to differences in the genes in the two species, and despite having the same number of chromosomes, meiosis is rarely successful in ligers. Ligers typically experience hybrid sterility or hybrid breakdown.

Interestingly, the liger tends to be larger than both its parents and is claimed to be the largest cat on Earth. All ligers have been bred in captivity because the natural ranges of tigers and lions do not overlap. The two species are naturally geographically isolated in the wild.

FIGURE 9.2.6 This liger is the hybrid offspring of a Siberian tiger (*Panthera tigris altaica*) and a lion (*Panthera leo*).

Another example is the bowerbird, which selects a mate based on the showiness, structure and colour of the bower it builds from collected objects (Figure 9.2.7). This again indicates the bird's health and fitness.

Animals may compete with members of their own sex for mates of the opposite sex. Animals such as sea lions, antelope and kangaroos come into direct physical conflict over mates, usually resulting in a single male winning the right to mate with a large number of females. These conflicts ensure that the individuals with the fittest phenotypes are most likely to produce more and healthier offspring after mating. In this way the fitter alleles are more likely to be inherited by the next generation and increase the frequency of those favourable alleles in the gene pool over time.

Sexual selection both produces and explains many striking features in animals and plants.

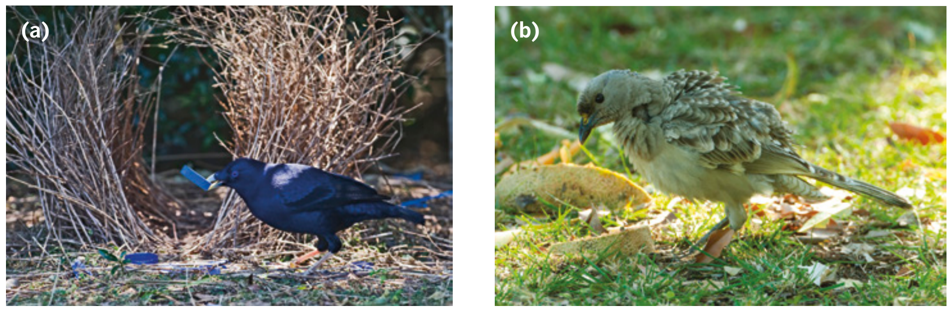


FIGURE 9.2.7 (a) Satin bowerbirds (*Ptilonorhynchus violaceus*) are found in wet forests in the southeast of Australia and are attracted to blue objects. (b) Great bowerbirds (*Chlamydera nuchalis*) occur in the more tropical ecosystems of northern Australia and are attracted to white, green and red objects. Although the species are also geographically isolated, this difference in mate attraction is an example of sexual selection and behavioural prezygotic isolation.

BIOFILE CCT

Sexual selection in birds

Sexual selection in birds has produced some of nature's most ornate and colourful features.

Vivid skin colouration such as that of the Australian brush-turkey or cassowary is largely cosmetic (Figure 9.2.8a, b). Except for attractiveness, such features arguably make no great functional difference to the animal's life.

Yet sometimes sexual selection results in traits that cause a distinct handicap. For example, many birds have evolved heavy, non-aerodynamic display feathers. The peacock is the classic example, but many other species, such as the lyrebird, have similar display plumage to attract females (Figure 9.2.8c).

Given the close relationship of dinosaurs to birds, it may be that some otherwise-puzzling dinosaur features have a sexual-selection explanation. The Hadrosaurs in particular had elaborate skull crests (Figure 9.2.8d). They would have been used to make loud honking sounds while probably also being very colourful.

Sexual selection often explains features that seem to have no adaptive purpose.

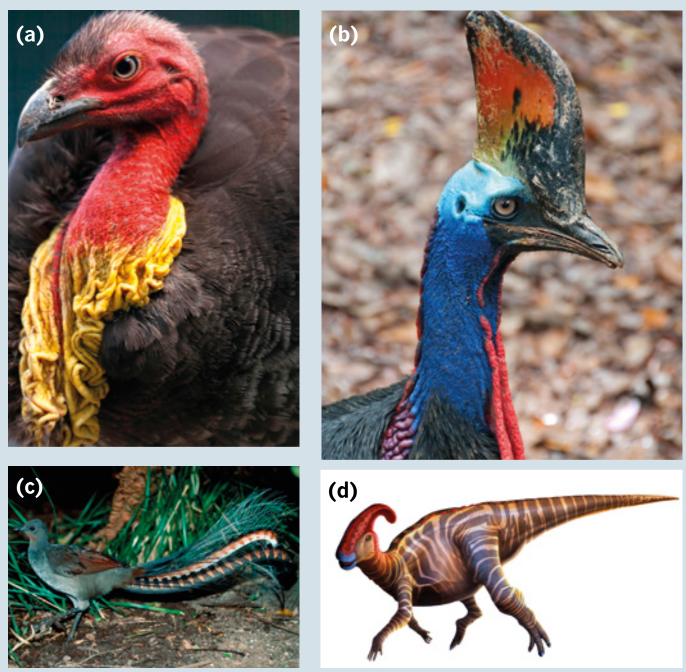


FIGURE 9.2.8 (a) The Australian brush-turkey (*Alectura lathami*), common in eastern New South Wales. (b) The southern cassowary (*Casuarius casuarius*), considered vulnerable in north-eastern Queensland. (c) The superb lyrebird (*Menura novaehollandiae*) male in courtship display, also common in eastern New South Wales. (d) *Parasaurolophus*, one of the more flamboyant Hadrosaurs from the Cretaceous period

SPECIATION

Speciation is the evolution of new species from an ancestral species. There are different evolutionary mechanisms that can lead to speciation; however, each of these mechanisms essentially results in an accumulation of genetic changes that leads to the reproductive isolation of populations. When populations become reproductively isolated, they can no longer interbreed and are considered distinct biological species.

Allopatric speciation

The most common form of speciation is **allopatric speciation** which occurs when a population becomes divided by a geographical barrier (Figure 9.2.9). The spatial isolation prevents individuals of the separated subpopulations from interbreeding.

Over time, different environmental selection pressures and genetic drift drive change in the allele frequencies of the two subpopulations. Eventually, the two subpopulations may diverge genetically and physically, to the point where they can no longer interbreed if they come into contact again. When populations can no longer interbreed, they are considered distinct species (speciation has occurred).

For example, as Australia moved northward approximately 56–23 million years ago, the centre became arid, which partitioned what had previously been a single continuous southern habitat into eastern and western zones. The species of each zone then continued evolving according to separate selection pressures, leading to the evolution of new local species. That is why the south-west corner of Western Australia has a very high number of **endemic** species, both plant and animal. Tasmania also has many unique species as a result of its separation (Figure 9.2.10). Tasmanian species diversified after Tasmania became separated from the Australian mainland following the rise in sea levels at the end of the most recent ice age.

Allele frequency refers to the proportion of the gene pool that carries a particular allele, relative to other alleles for that gene.

Genetic drift is the random changes in allele frequencies in a population. From one generation to the next, by random chance, some individuals will pass on more alleles than others, increasing the frequency of some alleles while decreasing the frequency of others.

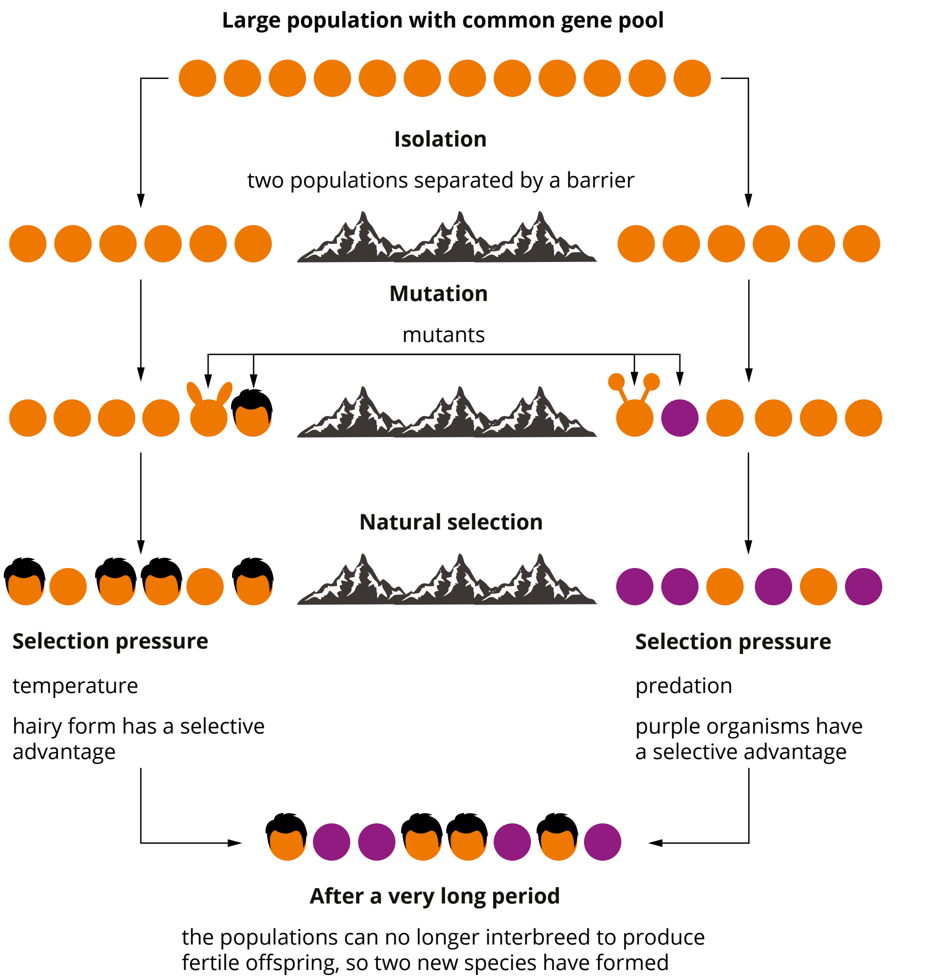


FIGURE 9.2.9 Geographic isolation can lead to allopatric speciation.

FIGURE 9.2.10 Tasmania has a high number of unique species that are not found on the mainland, such as the leatherwood (*Eucryphia lucida*).

BIOLOGY IN ACTION CC S

Allopatric speciation in the coast banksia

The coast banksia (*Banksia integrifolia*) is one of the largest and most common banksias on Australia's east coast. It grows as far north as Mackay in Queensland and as far south as Port Phillip Bay in Victoria (Figure 9.2.11). Over this extensive geographical range, populations vary in the shape of their fruits and particularly in their leaves.

Four forms have been identified. Researchers have recognised three of these forms as varieties or subspecies of *Banksia integrifolia.* The fourth form, *Banksia aquilonia*, was originally identified as another subspecies but is now recognised as a distinct species. Geographically, *B. aquilonia* is separated from the *B. integrifolia* subspecies by more than 200 km.

A molecular study using a DNA fingerprinting technique (called amplified fragment length polymorphism or AFLP technique) confirmed that the three *B. integrifolia* subspecies are genetically distinct from one another and different also from *B. aquilonia*. The technique also confirmed that plants with leaf shapes that are intermediate between the subspecies are the result of gene flow between populations. The distributions and characteristics of the species and subspecies of coast banksias are summarised in Table 9.2.1

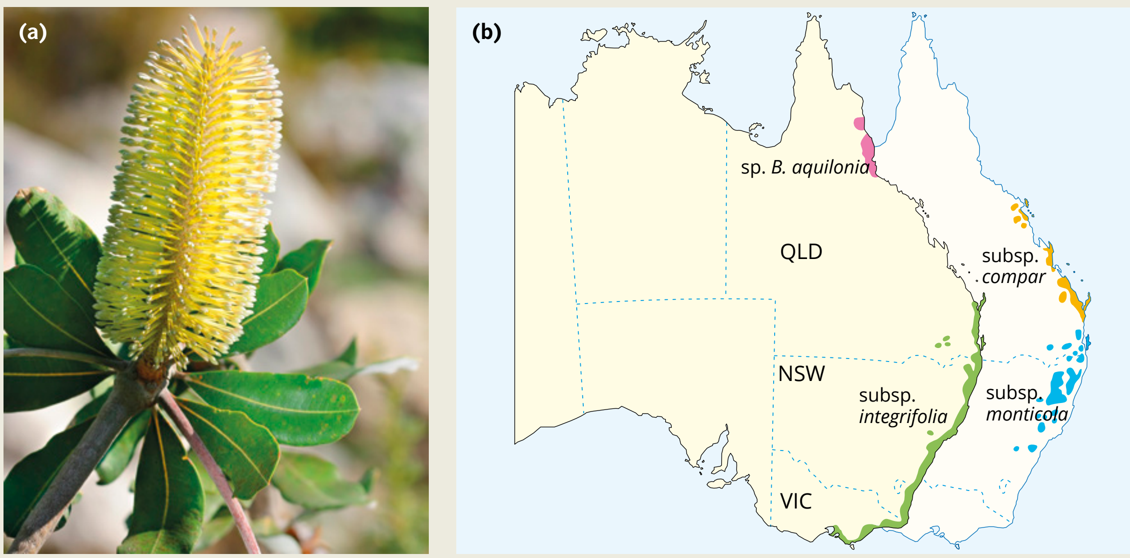
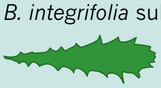


FIGURE 9.2.11 (a) Coast banksia, *Banksia integrifolia*. (b) The distribution of the different forms of coast banksia along the east coast of mainland Australia

TABLE 9.2.1 Distribution and characteristics of species and subspecies of coast banksias

Species and subspecies	Distribution	Form
B. integrifolia subsp. *compar* 	• scattered distribution, southern Queensland and north-eastern New South Wales, coastal	• large glossy adult leaves; seedling leaves elliptical, small straight side teeth
B. integrifolia subsp. *monticola* 	• south-eastern Queensland and north-eastern New South Wales, montane regions above 650 m in altitude	• narrow adult leaves; seedling leaves obovate (widest at the top), large teeth with curved sides
B. integrifolia subsp. *integrifolia* 	• southern Queensland, New South Wales, Victoria, coastal	• leaves shorter than *B. integrifolia monticola*; seedling leaves obovate, curved
B. aquilonia 	• north-eastern Queensland, coastal	• long narrow adult leaves; largest fruits, fringe of stiff hairs on the midrib, underside of the leaf

BIOLOGY IN ACTION CCT

Allopatric speciation of snapping shrimp

The Isthmus of Panama in Central America only arose approximately 3 million years ago. As a consequence of the Isthmus, two populations of snapping shrimp became separated with one population isolated on the North Pacific Ocean side and the other on the Atlantic Ocean side (Figure 9.2.12). A study carried out by Nancy Knowlton and her colleagues of the Smithsonian Tropical Research Institute found that the shrimp on each side of the Isthmus appeared almost identical to one another, suggesting that they had once been members of the same population. However, when Knowlton put males and females from different sides of the Isthmus together, they snapped aggressively instead of courting. The populations of snapping shrimp divided by the Isthmus had diverged and are now reproductively isolated due to the evolution of different courting behaviours. Biologists now recognise them as separate species, named *Alpheus nuttingi* (Atlantic) and *Alpheus millsae* (Pacific).

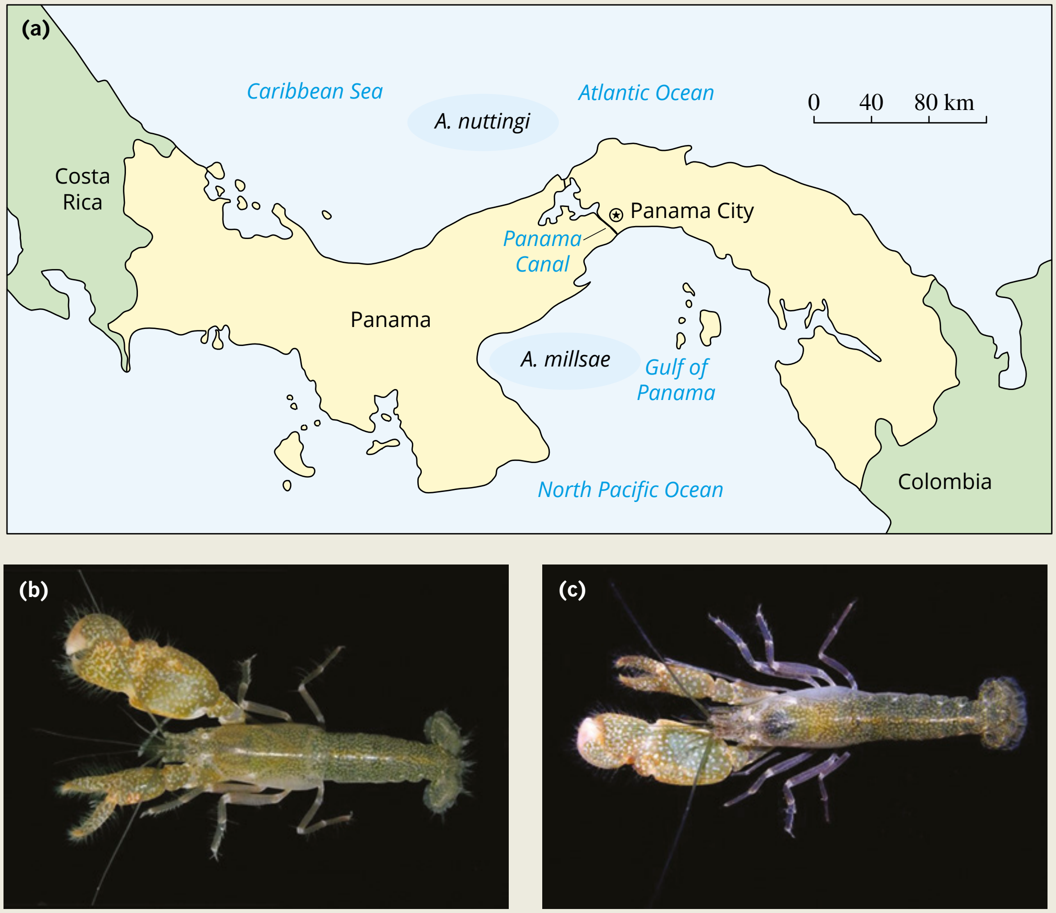


FIGURE 9.2.12 (a) The Isthmus of Panama, a geographic barrier, and the distribution of snapping shrimp isolated on either side. (b) *Alpheus nuttingi* and (c) *Alpheus millsae* are now recognised as two distinct species of snapping shrimp.

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Other forms of speciation

All forms of speciation require isolating mechanisms to prevent gene flow between populations. Geographical barriers, which lead to allopatric speciation, are the most common isolating mechanisms but there are others. Different isolating mechanisms result in different speciation processes.

Peripatric speciation

Peripatric speciation is similar to the process of allopatric speciation, but instead involves a small population on the edge of the range of a larger population. When this small population becomes spatially isolated from the main population, the founder effect (see page 410) can enable low-frequency alleles to become more common in only a few generations. The new population typically neighbours the original population and experiences similar environmental pressures. However, genetic drift occurs more quickly in smaller populations and so the new founding population becomes genetically diverse and evolves into a new species.

It is possible that the brown stringybark (*Eucalyptus baxteri*) and Mt Abrupt stringybark (*Eucalyptus verrucata*) species diverged in this way (Figure 9.2.4). Individuals on the edge of the forest ecosystem may have been pushed out to the rocky outcrops, typical of the Grampians, with shallower soil than found on the lower slopes. The difference in environmental conditions would have placed different pressures on individuals. Those with alleles that enabled them to survive in shallow soil would have been more likely to reproduce, and so those alleles would have increased in frequency. With enough time, this and other differences in environmental pressures would have resulted in speciation.

Sympatric speciation

Speciation can occur even when geographical barriers do not isolate populations. **Sympatric speciation** occurs when populations of a species that share the same habitat become reproductively isolated from each other. Sympatric speciation is more common in plants than in animals, and there are two ways in which it can occur.

Most habitats are made up of microhabitats, small areas with highly specific environmental conditions. When part of a population occupies a microhabitat, the difference in selection pressures can be enough to drive sympatric speciation. In this situation the two populations become genetically isolated by temporal or behavioural isolating mechanisms (see page 396).

Sympatric speciation in plants is more commonly caused through **polyploidy** (individuals with more than two sets of chromosomes). Polyploidy is caused by abnormal cell division which results in a change in the number of chromosome sets (e.g. from diploid, two sets of chromosomes, to tetraploid, four sets of chromosomes). If a mutation causes polyploidy in an individual, the polyploid plant can still reproduce successfully through self-pollination or vegetative reproduction. However, a polyploid plant is unlikely to successfully reproduce with its diploid counterparts and so sympatric speciation by polyploidy is instantaneous.

Parapatric speciation

Parapatric speciation is very rare. This form of speciation occurs where populations are not geographically isolated, but where there is significant variation in habitat conditions within the range of the original population. Gene flow is possible between the two populations; however, in a large population with a large range, individuals are more likely to breed with nearby individuals. Mating is not entirely random. Slight differences in environmental pressures from one end of the range to the other can result in localised variation in allele frequencies within the population. Over time, this may result in two distinct species. Although rare, this type of speciation has been seen in areas where the geographic range of species has formed a ring around an unsuitable habitat area.

Adaptive radiation

Adaptive radiation is the rapid divergent evolution of a large number of related species from a single common ancestor. Adaptive radiation results from accelerated speciation after organisms evolve different adaptations in response to new conditions and opportunities. This can occur following changes to the environment (e.g. extinction of competitors) or colonisation of a new environment where vacant ecological niches are available. Adaptive radiation can result in a wide diversity of species, each with unique adaptations to their environment.

Adaptive radiation is a type of divergent evolution where a group of organisms rapidly diverge into new species. 'Rapidly' in evolutionary terms may be 500 000 years or more.

The finches of the Galápagos Islands are an example of adaptive radiation. The beaks of these birds are adapted to different food types. Darwin collected specimens of finches from the different Galápagos Islands when he sailed on the voyage of HMS *Beagle* (1831–36) (Figure 9.2.13). When Darwin returned to England, the ornithologist John Gould examined the specimens and recognised them as related but distinct species. Darwin had collected 13 different species of finch, with every island in the archipelago home to a number of species. Each species has a particular beak, body size and feeding behaviour that is advantageous for the conditions on the island on which they are found. The various finch species had diversified from a single common ancestor; they had undergone adaptive radiation. The finches of the Galápagos Islands are also examined in Chapter 8.

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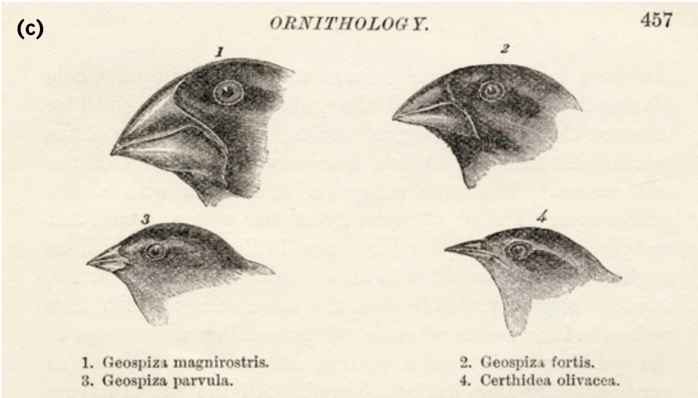

FIGURE 9.2.13 (a) Map of the Galápagos Islands. (b) The location of the Galápagos Islands relative to Central and South America. (c) Drawings of finch species by Charles Darwin. The numerous species were each native to a particular island, having undergone adaptive radiation from a single ancestor.

Australia also provides examples of adaptive radiations. The family Macropodidae includes 10 genera and 65 species (with some recent extinctions) including kangaroos, wallabies, wallaroos, quokkas, pademelons and tree-kangaroos (Figure 9.2.14). Macropods diverged from a common marsupial ancestor approximately 53 million years ago, with modern kangaroos radiating about 25 million years ago. For each genus today there are multiple species. The modern species have adapted to a browsing or grazing lifestyle with teeth and digestive systems specialised for feeding on plant material. This example of adaptive radiation, like most, occurred as multiple divergences over millions of years.

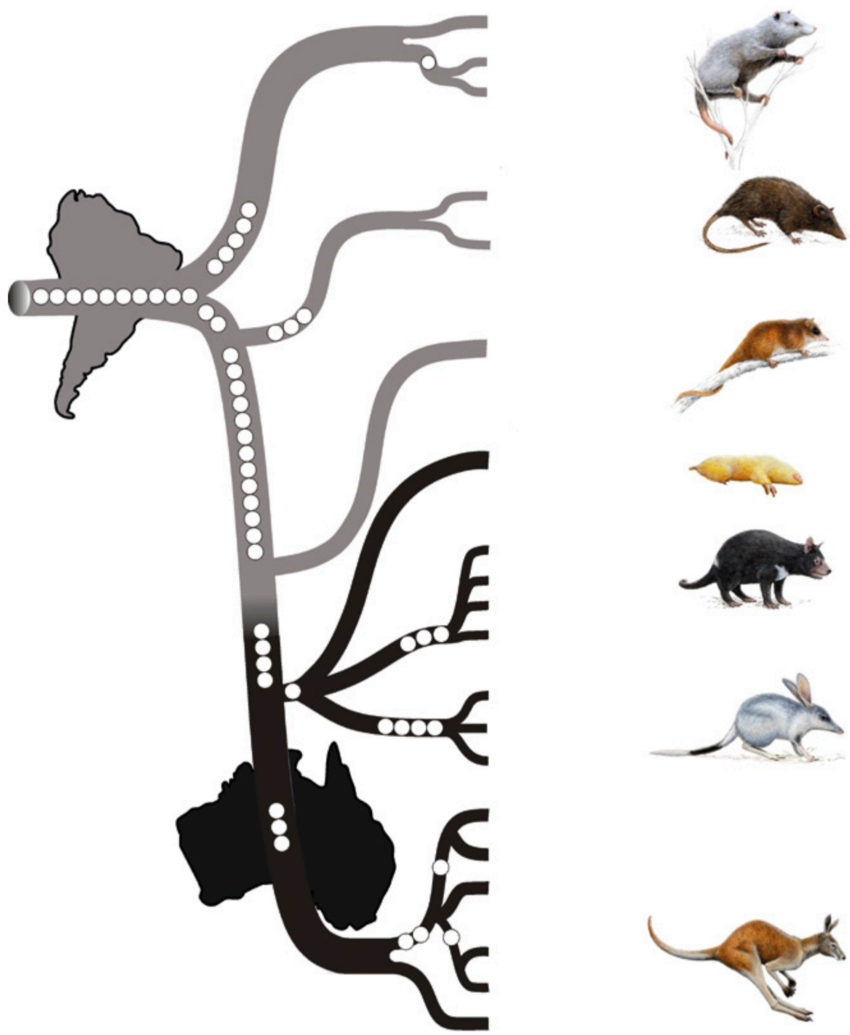

FIGURE 9.2.14 Evolutionary tree (or phylogenetic tree) showing the evolution of marsupials in South America and Australia. South America and Australia remained joined (via Antarctica), as a fragment of Gondwana, until about 167 million years ago.

MICROEVOLUTIONARY CHANGES

Microevolution involves changes in alleles, populations or species over short periods of evolutionary time. Mutation, migration, genetic drift and natural selection are the main processes that drive microevolutionary change. An accumulation of these changes over time can lead to speciation.

Evolution of the platypus

Australia's platypus (*Ornithorhynchus anatinus*) has been delighting and confusing biologists for centuries. Discovered in 1797, the European scientific establishment first thought the animal was a hoax.

Platypuses are mammals that have several primitive reptile-like features. Platypuses, plus the four species of echidna, are all that remains of an ancient group of egg-laying mammals called **monotremes**. Monotremes diverged from the main mammal lineage around 165–180 million years ago, during the Jurassic period. Platypuses and echidnas diverged between 48 and 19 million years ago.

Like its echidna relatives, platypuses lay soft, leathery eggs which they incubate next to their skin. Both groups also produce milk from pores in the skin, like sweat, in contrast to the **lactation** (milk production) through specialised nipples of other mammals. Uniquely, platypuses have a venomous spur on their hind legs, and have an extremely sophisticated bill capable of detecting the electrical impulse of prey animals.

The platypus fossil record is patchy. The oldest confirmed fossil of a platypus ancestor was found in New South Wales in 1985 and dates to around 110 million years ago, during the Cretaceous period (Figure 9.2.15). The next oldest fossil was a 62 million-year-old tooth found in Argentina. A further three fossils are all Australian, and date to 25–15 million years ago. The oldest fossil of the modern species is about 100 000 years old.

FIGURE 9.2.15 *Steropodon galmani*, an early platypus ancestor from the Cretaceous period

Such evidence suggests platypuses evolved in Australia when it was still connected to South America and Antarctica. A population of platypus relatives must have survived in South America for a time, but died out. Since then, platypuses have been confined to Australia. Recent genetic studies, comparing the modern platypus to other vertebrate groups, support the fossil evidence.

The new information confirms that many platypus features are truly primitive. For example, certain genes from egg-yolk proteins are shared only with reptiles and fish. Thus, egg-laying was retained from reptilian ancestors. Platypuses have a reptile-like cloaca, a single orifice serving both reproductive and excretory functions. Lactation also seems a very old feature, dating from the origin of the monotreme group during the Jurassic. Giving birth to eggless young (called live-bearing) was a much more recent feature developed by placental mammals.

The genetic analysis also shows that the platypus has put primitive reptilian genes to innovative uses. For instance, platypus venom appears to result from modification of genes that once served other purposes. While platypus and snake venom are similar, platypuses seem to have evolved the same feature but in a completely independent way via convergent evolution.

Some changes are recent accumulations and thus are described as advanced features. Today's platypuses are smaller than their ancestors, and this may be an ongoing speciation trend. Platypuses are substantially larger in Tasmania and southern Australia, becoming smaller towards the northern part of their range. Their populations may be diverging into northern and southern varieties.

The modern species also seems to have become more specialised for an aquatic lifestyle, plus its distribution has become restricted to Australian rivers (Figure 9.2.16). As part of this trend, the original teeth of the platypus have been replaced with horny pads, and there has been some anatomical simplification. Some recently evolved features also allow platypuses to smell while underwater, supplementing their electro-detection sense.

FIGURE 9.2.16 Platypus (*Ornithorhynchus anatinus*) swimming underwater. It hunts for shrimp, worms and insect larvae using sophisticated electro-detection and smell.

Evolution of the horse

Unlike the patchy fossil record for the platypus, the case of horse evolution is well documented. In fact it is one of the most complete **transitional series** in palaeontology.

A transitional series is a group of fossils showing microevolutionary change from one form to another. Each individual fossil is subtly different from the previous, like still images from a movie. Dramatic long-term transitions can result from a series of microevolutionary changes.

FIGURE 9.2.17 The ancestral horse species *Eohippus angustidens*, also called 'dawn horse', lived roughly 50 million years ago. They were about 20 cm tall at the shoulder and 60 cm in length, and walked on soft toe-pads rather than hooves.

The ancestral horse genus *Eohippus* (containing only one species, *Eohippus angustidens* arose around 52 million years ago (Figure 9.2.17). It was a wombat-sized rainforest animal, living much as tapirs (horse relatives) do now. Fossil teeth show that *Eohippus* was an unselective herbivore, eating mainly soft leaves and fruit. Its legs were much shorter relative to its body than modern horses, while its wrist and leg-joints were flexible. The animal had five splayed-out toes on each foot; a primitive feature retained from the common ancestor of mammals and still possessed by humans today who have five digits on each hand and foot. Four of the five front toes touched the ground, while at the rear *Eohippus* walked on the three middle toes. All toes had soft, pad-like hooves. *Eohippus'* teeth were generalised and fairly flat. *Eohippus* remained relatively unchanged for about 20 million years.

Towards the end of the Oligocene epoch, Earth started cooling and drying. Rainforest habitat slowly gave way to open forest, woodland and then grassland. The tougher vegetation favoured animals with sturdier grinding teeth (molars). At the same time, the increasingly open spaces would have selected for larger and faster animals able to evade predators.

The changing environment selected for various new traits through a series of slightly different species. The general trends included greater size, proportionally larger brains, improved running ability via loss of outer toes and weight being borne on the middle toe, stronger and longer leg and toe bones, more developed hooves, plus tougher teeth. Not all changes were gradual; for instance, high-crowned teeth suited to grazing appeared relatively suddenly. The extreme ends of the transition are shown in Figure 9.2.18.

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Evolutionary terms: primitive and advanced

Primitive in evolutionary terms means more like the original ancestor, and advanced means less like the original or more recently modified. Being labelled primitive does not mean that it is inferior, and advanced does not make it superior, just that it has evolved a different feature more recently. For example, in humans, feet and hands can be called primitive because they still have the original ancestral five digits. In the horse this feature has changed to become a single hoof and is described as advanced simply because it evolved more recently (Figure 9.2.18).

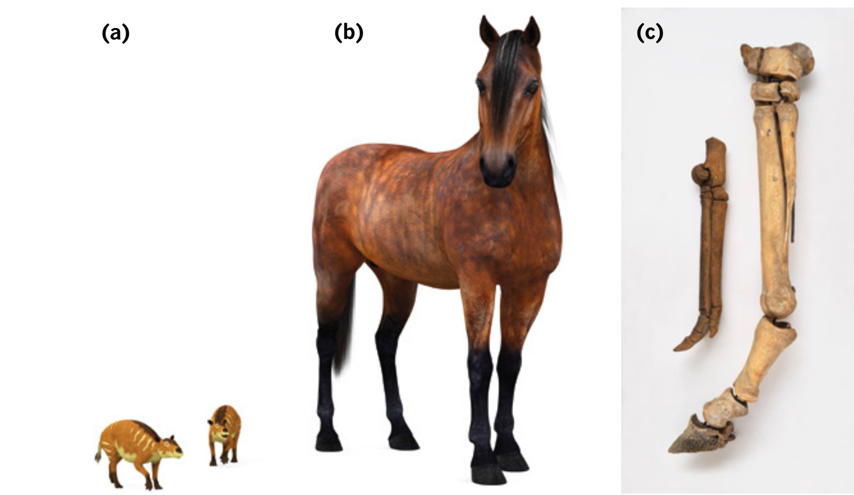

FIGURE 9.2.18 (a) Adult *Eurohippus* and (b) the artificially selected form of a modern horse. (c) Comparison of modern horse leg bones (right) next to those of an early horse (left) (note side toes)

Older textbooks presented the evolutionary journey from *Eohippus* to modern horses as a linear series as in Figure 9.2.19. Such texts also showed the human family tree in the same style.

FIGURE 9.2.19 The ancestral *Eohippus* (left) and transitional forms towards the modern horse (*Equus ferus przewalskii*, right). Not to scale.

However, this conventional image of evolutionary change as a linear series represents an incorrect understanding. Such transitions are extremely rare, and old-fashioned sequences such as this simplify the true complexity. Instead, adaptive radiation is the norm (Figure 9.2.20). Each new species would have been subject to new environmental and selection pressures, and rapid change according to punctuated equilibrium.

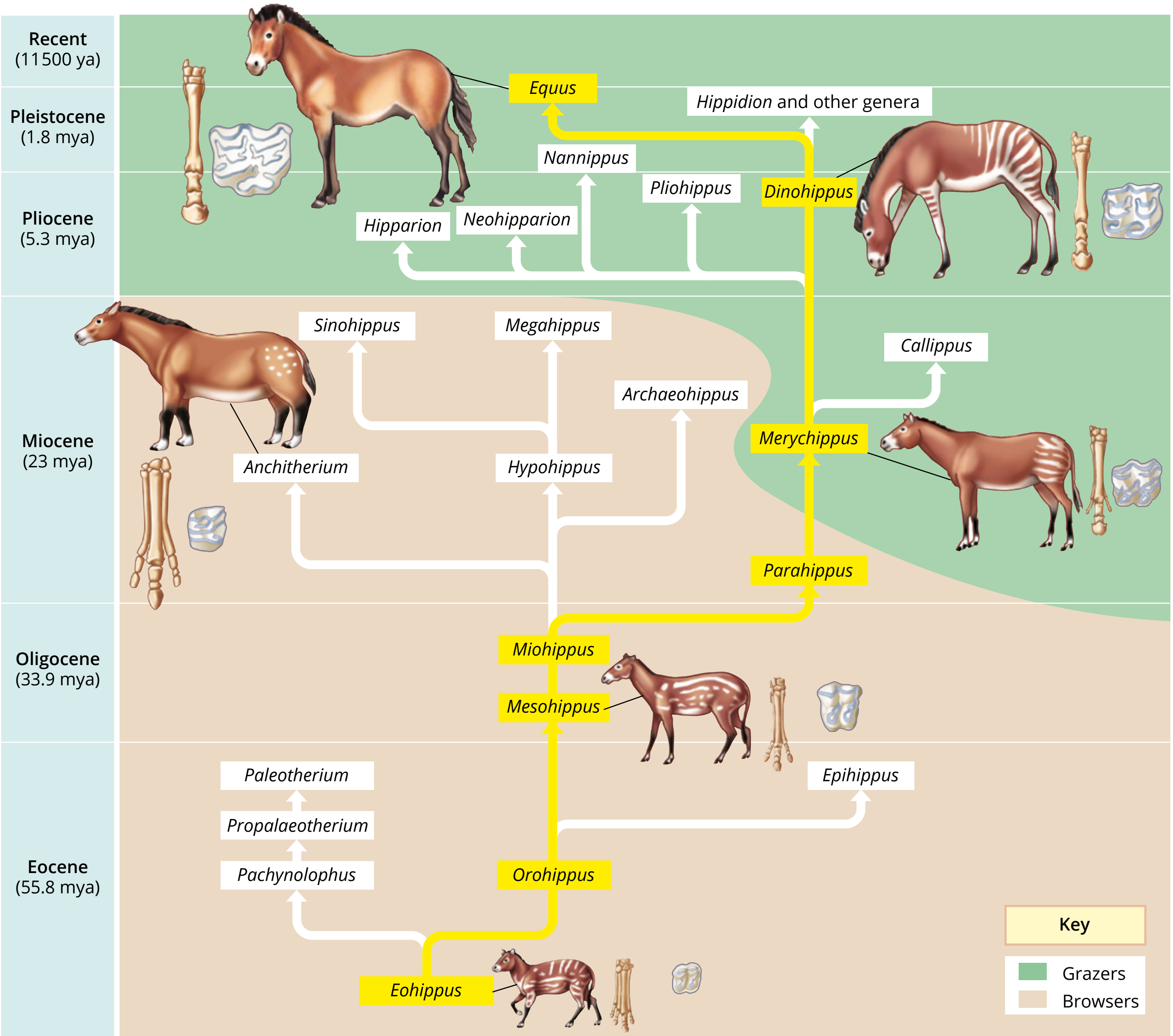

FIGURE 9.2.20 The branching of the horse family shown as an adaptive radiation rather than a linear sequence

Today, seven species remain from a family that was until recently even more diverse: three species of zebra, three asses (including donkeys), and the 'true horse' in both wild and domesticated forms (Figure 9.2.21). The latter group diverged from its nearest relatives as little as 43 000 years ago.

The fossil record of the horse family shows typical prezygotic isolation, speciation and adaptive radiation.

FIGURE 9.2.21 Przewalski's horses (*Equus ferus*), the wild form of the modern domesticated horse

Instant speciation

Modern horses are also examples of postzygotic isolation. At least some of the incompatibility between species results from chromosomal differences (Table 9.2.2). In the recent past these may have appeared via **instant speciation**. Sometimes chromosomes fail to separate properly during meiosis (this is known as a **nondisjunction**), resulting in offspring with an extra set of chromosomes (polyploid). Such individuals are chromosomally incompatible with other members of the herd. In most cases such individuals would be destined to never reproduce. However, if an affected individual found and mated with another member of the herd having the same number of chromosomes, the offspring may be viable. They would constitute a new species, phenotypically similar to the original but no longer reproductively compatible.

TABLE 9.2.2 The extant (still-existing) members of the *Equus* (horse) genus, with their different numbers of chromosome pairs. Although they are all very similar animals, chromosomal incompatibilities prevent interbreeding.

Species	Number of chromosomes (2*n*)
Horse	64
Mule	63
Donkey/ass	62
Grevy's zebra	46
Plains zebra	44
Mountain zebra	32

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Horse hybrids

The various species of horse vary mostly in temperament. Modern horses could be domesticated because they have a hierarchical social structure and a willingness to accept human dominance. Zebras, in contrast, are notoriously bad-tempered and aggressive. While donkey stubbornness may be something of a myth, donkeys are cautious and slow to make decisions, plus they are prone to loneliness-related depression.

Yet physically, all members of the modern horse family are essentially the same animal. They cannot successfully interbreed because of chromosomal incompatibilities (Table 9.2.2). Hybrid offspring do not have homologous pairs of chromosomes, having inherited one set from different species. In other words, horse hybrids are sterile.

The hybrids are still desirable in many ways. They exhibit what Charles Darwin observed as hybrid vigour: where hybrids have superior traits compared to their parents.

For example, mules (horse/donkey hybrids) are more patient than horses, calmer under heavy weights, generally tougher and resistant to horse diseases (Figure 9.2.22). They are also more intelligent than donkeys. Mules have a distinguished history as pack- and draught-animals.

FIGURE 9.2.22 A mule (left) is the offspring of a donkey (right) and a horse. However, the mule is sterile and cannot produce offspring of its own.

Some reports suggest that zebra/horse hybrids (known as zorses or zebrulas), and zebra/donkey hybrids (called zonies or zonkies) (Figure 9.2.23), are even better. They are immune to African horse diseases and insect pests such as the tsetse fly, and are tougher than mules but just as intelligent. Such zebra hybrids have gained employment as trekking pack animals in Kenya.

FIGURE 9.2.23 The zony is a hybrid resulting from the interbreeding of a zebra and a donkey.

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Genetic factors in evolution

Genetic drift

Allele frequencies in a gene pool may also change randomly over time as a result of chance events. This is called genetic drift. Genetic drift has more of an impact in small populations with little to no gene flow, as the random death of one individual can significantly alter the allele frequencies. Generally, in small populations genetic drift results in the loss of genetic variation over time as alleles are lost from the gene pool.

Genetic drift can occur when populations decrease for a period of time (a **bottleneck effect**) or in small founding populations (the **founder effect**).

Bottleneck effect

The number of individuals in a population can be drastically and quickly reduced as a result of a random event, often a natural disaster. Human activities such as hunting and land clearance have also greatly and quickly reduced the number of individuals in wild populations of plants and animals. For example, the mountain pygmy possum (*Burramys parvus*) has experienced population decline and reduced genetic variation due to habitat loss (Figure 9.2.24). The phenotype of an individual is unlikely to significantly increase its chances of surviving a natural disaster, such as a volcanic eruption, tsunami or landslide. The individuals that survive will do so by chance. The allele frequencies of the remaining population are unlikely to reflect those of the original population.

The bottleneck effect describes the impact on the remaining population. Because of the reduced population size, the possible reproductive pairings are limited, which leads to high levels of inbreeding. **Inbreeding**, or loss of genetic variation, results in reduced variation in the population. Alleles may also be lost from the gene pool immediately after the natural disaster or be bred out in only a few generations.

For example, the northern elephant seal, native to the Pacific coast of North America, was severely hunted during the 1890s. The population crashed to around 20 individuals. Although the numbers have since recovered to over 170 000, the population still has not yet regained its former genetic variability.

FIGURE 9.2.24 The mountain pygmy possum (*Burramys parvus*) has a declining population and reduced genetic variation. This population bottleneck is a result of bushfires and of habitat loss from land clearance and development around Mt Buller, Victoria.

This problem affects most threatened species. Such populations lack the genetic variation that natural selection draws upon, increasing the long-term risk of extinction as a result of environmental change. Low genetic variation can also reduce the biological fitness of populations and make them more vulnerable to disease. The Tasmanian devil (*Sarcophilus harrisii*) and the devil facial tumour disease are an example and are covered in more detail in Chapter 11.

Founder effect

The founder effect occurs when a small group of individuals from a larger population move to a new location and establish a new population. If a small portion of a population becomes separated from the original population, their smaller gene pool is unlikely to reflect the allele frequency of the original population. Like the bottleneck effect, there is increased inbreeding in the 'founder population' and lower variation.

In the new environment, the environmental pressures on the founder population are likely to be different from those experienced by the original population. These differences in environmental pressures drive further changes in allele frequencies and, ultimately, evolution.

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9.2 Review

SUMMARY

- A species is a group of individuals that can produce viable, fertile offspring through interbreeding. Its gene pool is isolated from the gene pools of other species.
- Gene flow is the movement of alleles into and out of a gene pool, such as when different populations interbreed or individuals migrate between populations.
- Interruption of gene flow partitions a population, leading to divergent evolution and speciation.
- Prezygotic isolating mechanisms prevent fertilisation of gametes of different species and include:
  - geographical isolation—physical barriers
  - ecological isolation—niche partitioning within an ecosystem
  - temporal isolation—differences in reproductive timing
  - morphological isolation—differences in reproductive structures
  - behavioural isolation (animals only)—differences in behaviours attracting mates, usually the result of sexual selection
  - gamete mortality—no fertilisation by gametes.
- Postzygotic isolating mechanisms prevent production of viable offspring after fertilisation and include:
  - hybrid inviability—the hybrid zygote does not survive
  - reduced hybrid viability—the hybrid zygote survives but does not develop fully into a new individual
  - hybrid sterility—the hybrid organism develops but is incapable of reproducing
  - hybrid breakdown—the hybrid cannot reliably produce viable offspring.
- Sexual selection involves competition for mates, chosen due to superior traits; this can produce elaborate behaviours or physical structures.
- Speciation is the evolution of new species from an ancestral species. The new species are genetically different enough from the ancestral one that interbreeding no longer produces viable offspring.
- Speciation involves either a variety of genetic isolation mechanisms between diverging populations or gradual changes in a single species over time, with differences in mutations, selection pressures and genetic drift changing allele frequencies and traits in the subpopulations.
- The most common form of speciation is allopatric speciation, where a population becomes divided by a geographical barrier. Spatial isolation thus prevents gene flow, causing genetic isolation and divergent evolution. Other forms of speciation are: peripatric, sympatric and parapatric speciation.
- Adaptive radiation is a form of divergent evolution where a common ancestor leads to many new species rapidly, particularly when a change in the environment opens new environmental niches.
- Evolution is usually due to microevolutionary changes. The platypus and horse show how such changes can lead to different forms and speciation over time.
- The platypus is a primitive mammal that retains numerous reptilian features but also evolved advanced new features from ancient reptilian genes. They may be undergoing speciation into northern and southern forms.
- Horses are an example of speciation due to changing environments and selection pressures. Horse ancestors diverged and speciated many times due to a drying climate, with selection favouring larger animals able to eat tough grass and run to avoid predators. Their toes and hooves also evolved. Modern horses demonstrate postzygotic isolation and hybrid sterility.
- A number of genetic factors can have magnified effects on small, isolated populations, causing additional selection pressures:
  - genetic drift—a change in the genetic make-up of a population due to chance rather than natural selection
  - bottleneck effect—population size (and genetic variation) is significantly reduced by an event, often a natural disaster, and can lead to increases in inbreeding
  - founder effect—a small group of individuals breaks away from the main population and colonises a new habitat. The founding population usually has less genetic variation than the original population and experiences different selection pressures in the new environment.

9.2 Review *continued*

KEY QUESTIONS

1. How might gene flow occur between two populations?
2. Australia's southern boobook (*Ninox boobook*) (Figure 9.2.3a) is closely related to the New Zealand morepork (*Ninox novaeseelandiae*) (Figure 9.2.3b). The two species are separated by a geographical barrier. If you attempted to crossbreed a morepork owl with a southern boobook owl, what could you assume about their offspring?
3. In hybrid inviability, why does the zygote fail to develop?
4. Why is genetic isolation an important step in speciation?
5. Other than genetic isolation, what two other factors are required for speciation to occur?
6. Give some examples of conditions that can result in allopatric speciation.
7. Complete the following sentences.
   Adaptive radiation is a form of ____________ evolution. It occurs when several species evolve from a single ____________ ancestor. Adaptive radiation is a result of rapid ____________ that can occur following changes to the ____________. Vacant ecological ____________ provide new opportunities, and organisms may ____________ in different ways to different conditions and diversify.
8. **a** Summarise the key trends in the evolution of modern horses.
   b Explain the adaptive significance of the changes.
9. Would genetic drift have more impact on a small population or a large one?

9.3 Macroevolution and biodiversity over time

Today, Earth is very different from when it formed over 4600 million (4.6 billion) years ago. Starting as a totally molten and lifeless world, it has passed through many different phases driven by a mix of biological and geophysical forces. Significant events included a long period of intense volcanism that helped create complex molecules and life, a toxic gas added to the original atmosphere, numerous ice ages including a completely frozen world, ocean acidification, continental pile-ups, a planet-wide desert and vast tropical forests. Since the origin of biomolecules, the first cellular life in the oceans and the formation of a solid surface on Earth (Figure 9.3.1), living organisms have been constantly responding to environmental change. This change drives the evolution of life on Earth; constant conditions would mean little or no evolution. Environmental change can lead to the extinction of some species but bring new opportunities for others.

FIGURE 9.3.1 When Earth formed 4600 million years ago, it was completely molten. It took many millions of years to cool enough for a hard surface to form, nearly all of which was soon covered with ocean.

Macroevolution means change above the species level. It is separate from microevolution (changing allele frequencies within a species). The processes are not fundamentally different: macroevolution is essentially the cumulative results of microevolution over very long periods. As such, life has become more complex since it first appeared on Earth.

In this section you will learn about the significant changes in life forms over Earth's geological history, including the evolution and diversification of multicellular organisms, land animals, the first flowering plants, and mammals.

GEOLOGICAL TIME SCALE OF EARTH

The history of Earth and evolving life can be traced using the **geological time scale**, which covers events that occurred on Earth from its formation to now.

Cliff faces often show layered sequences of different-looking rocks, each with specific collections of fossilised remains of ancient organisms within the rock strata (singular **stratum**) (Figure 9.3.2). The layering of the various strata is consistent across sites around the world. These features help us reconstruct Earth's geological history.

The first such histories relied on relative dating. Sedimentary rocks are deposited in a top-down direction, like layers of snow on a ski slope. Therefore, those at the top must be youngest while the oldest are at the bottom. For much of the history of geology, the layers could only be compared as older or younger than those adjacent, and the actual ages were unknown. Since the advent of **radiometric dating**, the exact ages of the rocks can be measured.

FIGURE 9.3.2 (a) Geological layers can be seen at Fossil Cove, Tasmania, Australia. (b) Ammonite fossils embedded in rock

The geological time scale is divided into many subdivisions, the largest being **eon**. Eons are subdivided into smaller and smaller divisions: **eras**, **periods** and **epochs** (Table 9.3.1).

TABLE 9.3.1 Geological time scale in millions of years ago (mya)

Eon	Era	Period	Epoch	Age (mya)	Plant life	Animal life
Phanerozoic eon	**Cenozoic**	Quaternary	Holocene	0.01	• modern plants	• evolution of humans
			Pleistocene	2.58		
		Neogene	Pliocene	5.33	• angiosperms dominate forests and grasslands	• mammals diversify, including primates • whales appear in oceans
			Miocene	23.03		
		Palaeogene	Oligocene	33.9	• angiosperms continue to dominate	• many primate groups appear
			Eocene	56	• angiosperms continue to dominate	• mammals continue to diversify
			Palaeocene	66	• angiosperms continue to dominate	• mammals, birds and pollinating insects diversify
	Mesozoic	Cretaceous		145	• angiosperms become dominant	• dinosaurs become extinct • mammals diversify or further develop • birds diversify • first primates
		Jurassic		201.3	• conifers abundant, first angiosperms	• age of reptiles, some flying reptiles • first birds
		Triassic		252.2	• conifer trees dominate forests	• first mammals • first dinosaurs • reptiles dominate land • amphibians decline
	Palaeozoic	Permian		298.9	• early seed plants develop, including cycads and early conifers	• reptiles diversify • familiar insects develop • many land vertebrates • many invertebrate sea life become extinct
		Carboniferous		358.9	• first large swamp forests of vascular land plants	• insects become more common • first reptiles
		Devonian		419.2	• tree-like vascular land plants, including lycopods; ferns appear	• fishes and coral reefs common
		Silurian		443.8	• first small vascular land plants, many algae	• many coral reefs, shells • first animals on the land—amphibians and invertebrates
		Ordovician		485.4	• types of large algae found as fossils	• many invertebrates • first vertebrates—fishes—found
		Cambrian		541	• more types of algae appear	• animals with bodies protected by shells • first fishes appear
Proterozoic eon		Ediacaran		635		• soft-bodied animals • a few fossils found of animals with jelly-like bodies
		Cryogenian		720	• *Amoeba* • algae	
				2500	• multicellular life develops in shallow warm seas • fossils rarely found, due to the age of the rocks and the soft fragile bodies of these organisms	• first animal traces

Eon	Era	Period	Epoch	Age (mya)	Plant life	Animal life
Archaean eon				4000	• bacteria (prokaryotes) abundant • fossilised and living stromatolites are still found on Earth today • oldest known sedimentary rocks, and oldest 'fossil' remains—chemical traces of living things	
Hadean time				4600	• solidification of the Earth from a ball of molten rock	

Note: The Proterozoic eon, Archaean eon and Hadean time are collectively known as Precambrian time. Hadean time is not a geological era/eon/period.

PRECAMBRIAN TIME

Although the Cambrian did not begin until the most recent fifth of Earth's history, when Earth was already over 4000 million years old, the period has special significance for geologists and biologists. For many years, it seemed that rocks from this period contained the oldest fossils of complex creatures. According to pre-20th century science, fossils were seemingly absent from earlier periods and some scientists had wondered whether life spontaneously appeared during the Cambrian. We now know that macroscopic life appeared much earlier than the Cambrian, and that instead of being the origin of life, the Cambrian merely marked the origin of hard body parts that easily fossilise.

Precambrian time is not a true geological eon, era, period or epoch. The Precambrian is divided into three parts: the Hadean, the Archaean eon and the Proterozoic eon. Life on Earth first appeared during the Archaean eon.

FIGURE 9.3.3 The surface of Earth as it may have appeared beneath its clouds during the Hadean, when volcanoes and lava fields still dominated the landscape

The Hadean (~4600–4000 mya)

Earth had formed by 4600 million years ago. Planets form by attracting planetesimals (space rocks) via gravity; the high-speed collisions impart enough energy to melt the entire mass. Earth was molten at first, and remained so for a further 600 million years. This was the Hadean time, named after the mythological Hades underworld, of 4600–4000 million years ago.

The molten rock released into the atmosphere much of the water that had been part of its source material. As the planet gradually cooled, molten material solidified, creating a rocky terrain (Figure 9.3.3). During this cooling period, the atmospheric water condensed, falling as a colossal rainstorm lasting millions of years. The water helped cool the surface, eventually enough for the water to pool permanently as oceans.

The Hadean is technically not a geological period as no terrestrial rocks survive from this time. Estimation of the time of Earth's formation is based on the age of lunar rocks from the Apollo 16 mission in 1972, dated to approximately 4500 million years. The Moon is of similar age to Earth, but slightly younger. The Moon formed from a collision between Earth and a Mars-size proto-planet, very early in Earth's history. Meteorite samples also provide a consistent age for the rocky material of the inner solar system, collectively pointing to Earth's age being about 4600 million years.

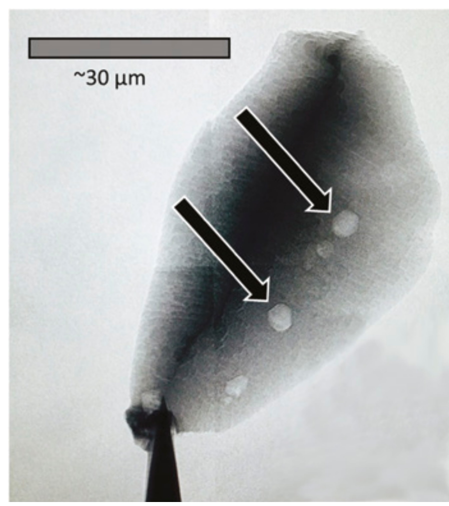

FIGURE 9.3.4 Transmission X-ray image of detrital zircons (from Jack Hills, Western Australia) showed the presence of pure carbon (graphite) in two locations, shown by the black arrows. Tests show the carbon is around 4400 million years old.

Earth's oldest rocks are roughly 3800 million years old. Although solid rock formed earlier, erosion and **plate tectonics** have since destroyed all of Earth's oldest rocks. Yet grains from such rocks survive, and have since been incorporated into younger rocks. Called zircons, these grains have been dated to 4400 million years (Figure 9.3.4).

The advent of a rock record marks both the start of Earth's geological history and the beginning of the Archaean eon.

Archaean eon (4000–2500 mya)

The Archaean eon spanned about 1500 million years. At the time the atmosphere was mainly carbon dioxide, methane and ammonia. At the start of this eon, the atmosphere had neither free oxygen nor nitrogen, because both gases are by-products of life. What little land existed consisted of many small island proto-continents called cratons.

Life appeared early in the Archaean. The earliest free-living cellular life forms not bound to geophysical structures were bacteria, soon followed by a related but different kind of prokaryote called archaea.

The oldest fossils are microfossils of bacteria that are roughly 3800 million years old. **Stromatolites** came after these earliest life forms but since they fossilise easily, they became common in the fossil record around 3500 million years ago. Stromatolites are mats of sticky photosynthesising bacteria, which grow on the outer surface and collect sandy material. Because stromatolites collect layers of sediment, they form characteristic layered fossils. Stromatolite fossils in cross-section contain many thin mineral layers (Figure 9.3.5a). They have been found in early Archaean rocks of South Africa and Western Australia (Figure 9.3.5b) and increased in abundance throughout the Archaean, but began to decline during the Proterozoic eon. Stromatolites still exist today, most famously in Shark Bay, Western Australia (Figure 9.3.5c).

The two main kinds of early prokaryotes (archaea and bacteria) were Earth's sole inhabitants for more than 1500 million years.

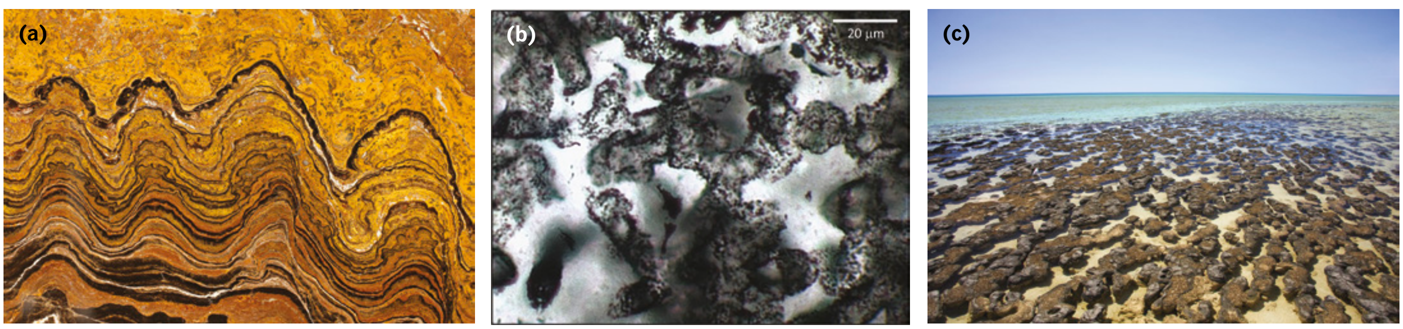

FIGURE 9.3.5 (a) Section through a rock with layers of fossilised stromatolites. (b) Microfossil of bacteria that lived 3400 million years ago found in sandstone at the base of Strelley Pool, Pilbara region, Western Australia. (c) Stromatolites can still be found today at Shark Bay, Western Australia.

THEORIES ON HOW LIFE CAME ABOUT

At some point, organic molecules accumulated to form the first self-replicating life form. We know that life depends on elements including carbon, hydrogen, nitrogen, oxygen, phosphorus and sulfur, and that water is vital. Several theories about how life first began are currently being investigated.

Often in science, new theories disprove and replace old theories, but in this case two older theories—the primordial soup theory and the RNA world theory—are both partially correct and are now part of a more complete theory: the hydrothermal vent theory. The hydrothermal vent theory is our best current understanding of the origins of life on Earth.

The primordial soup theory

The primordial soup theory suggested that **amino acids** (the building blocks of proteins) were the result of gases from early Earth's atmosphere and molecules in the vast oceans being energised and changed by lightning strikes and ultraviolet light. This theory was proposed independently by Russian scientist Aleksandr Oparin and English geneticist John Haldane, and is often referred to as the Oparin–Haldane theory.

Many scientists have attempted experiments to replicate the conditions of early Earth and produce amino acids, most famously Stanley Miller and Harold Urey in the USA in 1953. The Miller–Urey experiment produced organic compounds, including amino acids, using a closed system of laboratory equipment to model the primordial environment (Figure 9.3.6).

As our understanding of the ancient atmosphere and weather has developed, it has become clear that the significance of the Miller–Urey experiment lies in demonstrating that organic molecules can be made from inorganic molecules.

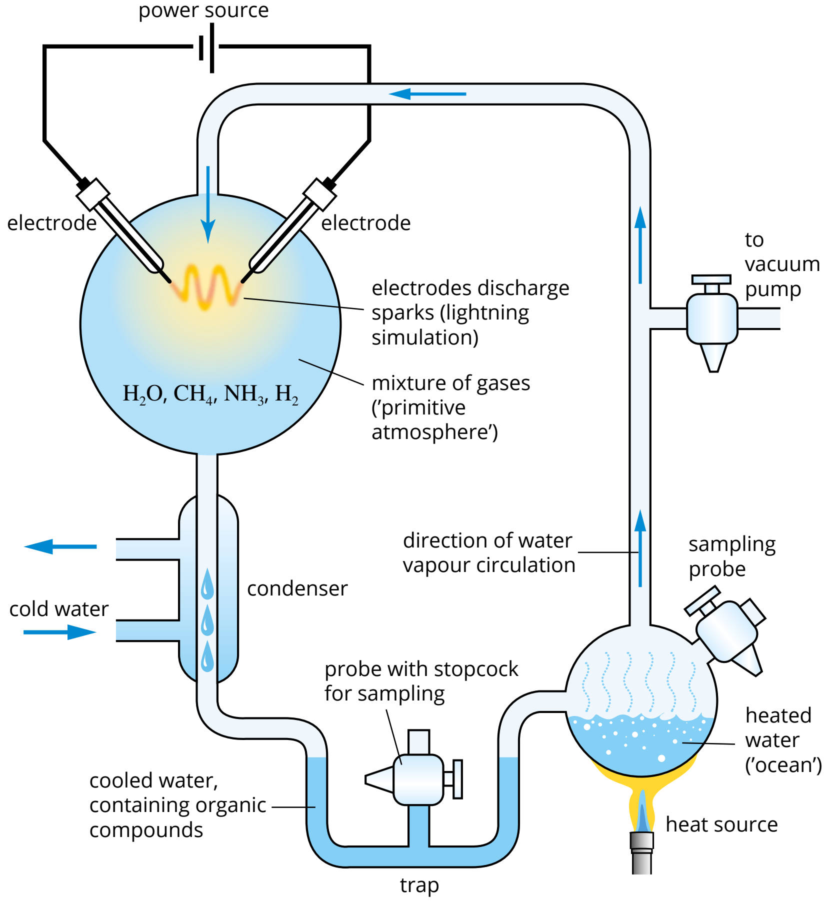

FIGURE 9.3.6 The Miller–Urey experiment

The RNA world theory

All living cells on Earth contain the following three biomolecules, each serving a different critical function:

- proteins—made of amino acids; they have structural and catalytic functions
- DNA—double-stranded nucleic acid that carries information from one generation to the next
- RNA—single-stranded nucleic acid that carries information and has metabolic functions within a cell.

In the early 1980s Sidney Altman and Thomas Cech found that some RNAs can act as catalysts for chemical reactions. These catalytic RNAs are known as ribozymes, and earned them the 1989 Nobel Prize in Chemistry.

The discovery of ribozymes supported a theory that RNAs were the first molecules able to store information, replicate and catalyse reactions. Due to the instability of RNA, DNA may have eventually evolved to become the dominant genetic material.

Hydrothermal vents theory

Convection currents within Earth push the crustal plates around the planet's surface. The plates move past or under each other in various ways.

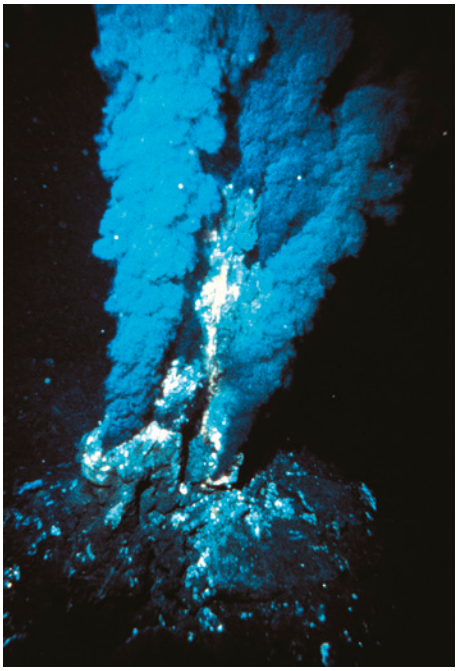

FIGURE 9.3.7 A black smoker hydrothermal vent on the Atlantic floor. Many hydrothermal vents support ecosystems based on bacteria that use volcanic gases as a source of energy, so are independent of solar energy.

Some pairs of plates also move apart in opposite directions, driven by upwelling lava. Today, such sites are nearly always in the deep ocean, so the plates are saturated with water. Around the sites of lava upwelling, the highly mineralised water is very hot. The water rises, and following contact with cold seawater, the minerals precipitate out to form towers up to 60 m tall. This process resembles smoke rising, so two of the three kinds of towers are called smokers (black smokers or white smokers) (Figure 9.3.7). Today, the smoker towers are very rich in life, although life did not originate there.

A third kind of tower, discovered in 2000, occurs up to 10 km from lava fields. The rising water is cooler—150–200°C compared to 450°C for the smoker towers. The water deposits carbonate mineral structures, and from their appearance they are known as Lost City Hydrothermal Vent Fields (Figure 9.3.8). These have a spongy, cell-like texture. The mineral walls are porous to water, but not to large molecules.

The combination of heat and pressure builds many complex organic molecules, inside the mineral cells, from water and carbon dioxide. Also, the Lost City structures are highly alkaline, and seawater is less alkaline, setting up a steep ion gradient that is effectively a powerful electric current. With this power source, and given that water continually circulates through the Lost City towers, the biomolecules become increasingly complex. This process combines both the Miller–Urey experiment principles and those of the RNA world theory. The current evidence from the Lost City towers suggests that geophysical forces alone produced metabolic processes.

Metabolic processes preceded life. Life merely incorporated the existing chemical pathways. The metabolism at first occurred only within the Lost City structures. At some point, the metabolism became complex enough to be fully self-replicating while also consuming material from the environment. So the simplest kind of life was born, although completely tied to the Lost City structures.

In the steps leading to the evolution of the biological cell, replicating organic molecules became enclosed in vesicles, surrounded by a biological membrane. The membrane provided an internal environment that was different from the external environment and in which metabolic processes could develop.

After developing membranes, eventually free-living cells moved away from the Lost City towers. Yet they kept the chemistry of the original structures, including chemically reproducing the necessary electric current.

The hydrothermal vent theory is also the only one compatible with the fact that Earth completely froze over during the Cryogenian period. Life in the deep ocean volcanic vents had no need of sunlight and was unaffected by the frigid surface conditions.

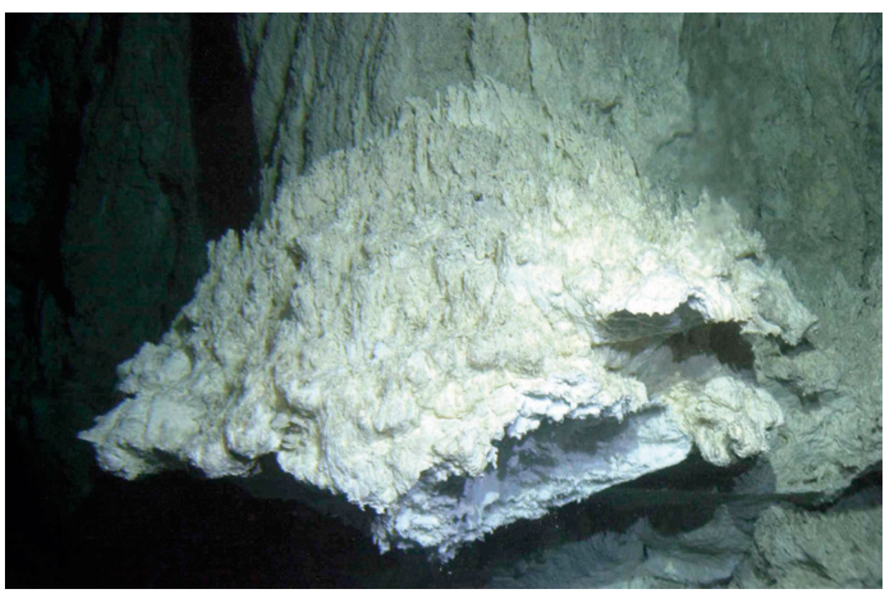

FIGURE 9.3.8 A 1.5 m wide ledge on the side of a Lost City Hydrothermal Field tower from the mid-Atlantic. Similar sites probably hosted the origin of life.

Evolution of cellular organisms

The two earliest forms of cellular life were bacteria and archaea, both prokaryotes. The two forms look very similar, and neither has any visible organelles; yet chemically they are quite different, with archaea closely resembling eukaryotic metabolism and membrane biochemistry. As stated by the **endosymbiotic theory**, it is now clear that bacteria entered archaean cells, but were not consumed, and continued to live. The combination of both types of prokaryotes was effectively the birth of eukaryotic cells that were more metabolically efficient. The endosymbiotic theory is discussed in more detail in Chapter 2.

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The mitochondria and chloroplast organelles of eukaryotic cells are effectively simplified bacteria in a symbiotic relationship with the cell. Both types of organelle maintain their own DNA, independent of the cell's nuclear DNA. Cellular nuclear membranes probably developed from infolding of the bacterial cell membrane, enclosing the bacterial DNA.

Eventually, eukaryotic cells started joining together in colonies of a single type of cell, working as one. That was the origin of multicellular organisms. Such organisms further developed specialised cells for various functions.

PROTEROZOIC EON (2500–541 MYA)

During the Proterozoic eon, large continental landmasses were formed by the convergence of smaller cratons. The stromatolite-forming bacteria, plus other species similar to modern **cyanobacteria** (formerly called blue-green algae) had been photosynthesising since the Archaean. Photosynthesis uses light energy to make sugars from carbon dioxide and water, with oxygen being a by-product. At first oxygen gas made no difference to the atmosphere. Iron in the sea reacted with oxygen, removing oxygen from the air and forming iron-oxide sedimentary layers in the deep ocean. After many millions of years, the iron in the sea was used up and oxygen then started building up in the atmosphere.

By about 2000 million years ago, the atmosphere was rich in oxygen. This caused the extinction of many early anaerobic life forms because oxygen was toxic to them. However, oxygen in the atmosphere allowed for the evolution of aerobic and complex multicellular life forms. The earliest eukaryotes are known from fossils 1400 million years old. Multicellular algae (red algae and green algae) and the first animals evolved towards the middle of the Proterozoic eon.

One reason it took complex life so long to appear was that the supporting structural molecules that eukaryotes and multicellular organisms needed to grow larger can only exist in an oxygen environment. Evolution was limited until the atmosphere became oxygenated.

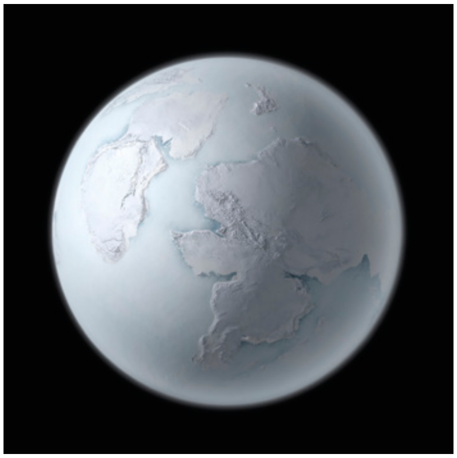


FIGURE 9.3.9 Sturtian glaciation, Cryogenian period, better known as the Snowball Earth

The Cryogenian period (720–635 mya): Snowball Earth

Geological evidence from the Cryogenian period of the middle-Proterozoic shows severe glaciation across the whole planet, even on continents near the equator at the time. This is currently interpreted as two separate phases of total ice coverage during the Cryogenian, both of which also froze the oceans to a considerable depth (Figure 9.3.9).

However, life at the bottom of the oceans, powered by volcanic energy, was hardly affected. This period saw the emergence of *Amoeba*, red and green algae, and sea sponges.

FIGURE 9.3.10 Traces of fossilised sea jellies can be seen in rippled sandstone in the Flinders Ranges, South Australia.

The Ediacaran period (635–541 mya): multicellular life diversifies

The Ediacaran period, at the end of the Proterozoic eon, reveals the earliest evidence of diverse multicellular animals. These animal fossils are collectively called the Ediacaran fauna after the Ediacara Hills in the Flinders Ranges of South Australia where they were first found in 1946 (Figure 9.3.10). The fauna has since been recorded from all continents. The fossils are of small, soft-bodied sea creatures

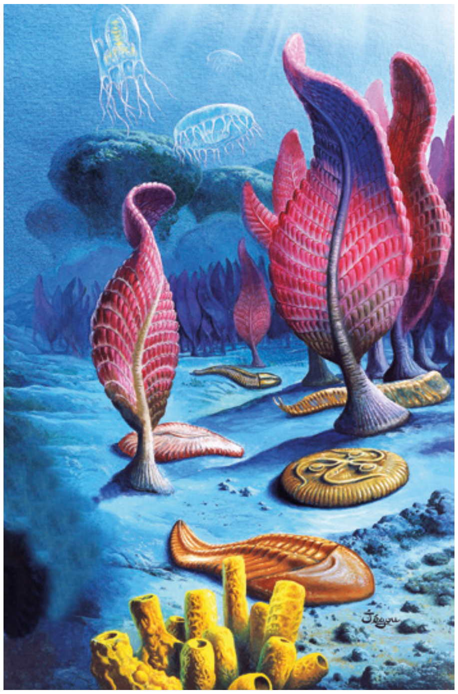


FIGURE 9.3.11 Ediacaran organisms, or the first multicellular animals. These included *Dickinsonia* (red), *Tribrachidium* (disc-shaped, yellow, centre right) and *Spriggina* (orange).

that resemble modern jellyfish, segmented worms, and animals with plant-like branching forms (Figure 9.3.11). They include representatives of all the major groups of invertebrate animals, plus some unique to the period. The fauna was entirely aquatic, and mostly benthic (bottom living) but also fixed in place rather than free swimming. The atmosphere of the time had low oxygen but very high carbon dioxide compared to today.

THE PALAEOZOIC ERA

The Palaeozoic (meaning 'ancient life') was a time of great change for Earth. By the early Palaeozoic, Earth's landmasses had combined to form a single supercontinent: **Pangaea**. These movements of land masses greatly affected the climate as well as land and sea environments, and hence the evolution of organisms.

Cambrian period (541–485.4 mya): the Cambrian explosion

Fossil evidence from 542 million years ago shows a dramatic increase in the number and complexity of life forms in the oceans. This is known as the **Cambrian explosion**. Fossils include worms, sea jellies, brachiopods and arthropods, the most common being trilobites (Figure 9.3.12). The number and diversity of Cambrian fossils is significantly greater than those from the Ediacaran period due to the emergence of organisms with hard exoskeletons, which are more readily preserved.

FIGURE 9.3.12 Fossils from the Cambrian period. (a) Trilobite fossils from the Czech Republic. (b) Fossil sponge (*Vauxia gracilenta*) from the Burgess Shale formation in Canada. (c) *Hallucigenia fortis* invertebrate (red) and sea jellies swimming in an ancient sea during the Middle Cambrian. (d) Illustration of a collection of trilobites on a sea bed

BIOFILE CCT

The Burgess Shale

The Burgess Shale in the Canadian Rocky Mountains is a significant fossil site from the Cambrian because it provides a rare glimpse of soft-bodied animals. The Burgess Shale was deposited in the ocean near an underwater algal reef shelf, where occasional undersea landslides buried animals. The fine mud prevented decay, preserving the animals' soft parts. As a result, the Burgess Shale provides a large record of extinct soft-bodied organisms. The deposit also preserved parts of many shelled animals not normally seen in other fossil records, including the legs and antennae of trilobites and the setae (hair-like structures) of brachiopods (Figure 9.3.13).

FIGURE 9.3.13 Brachiopod *Lingulella waptaensis*, from the Burgess Shale, Canada

Ordovician period (485.4–443.8 mya): the first vertebrates

The Ordovician was a time of very warm water (45°C), high sea levels and extensive shallow seas rich in algae. Simple, non-vascular land plants may have started colonising the shoreline.

The fauna diversified. Major groups included straight-shelled nautiloids, and various types of arthropods including trilobites (Figure 9.3.14). Reef-forming corals appeared during this time. Other newcomers included the first vertebrates: jawless armoured fishes (ostracoderms) (Figure 9.3.15).

Volcanic activity at the end of the period deposited silicate rocks that absorbed atmospheric carbon dioxide. The lowered temperatures introduced a brief but extreme ice age, which dropped sea levels, thereby dramatically impacting coastal habitats. The end of the Ordovician was Earth's second-largest **mass extinction**.

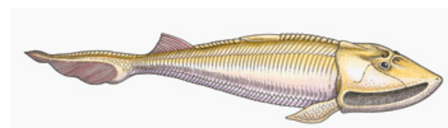


FIGURE 9.3.15 *Cephalaspis*, an armoured fish that belonged to the group of jawless vertebrates called ostracoderms

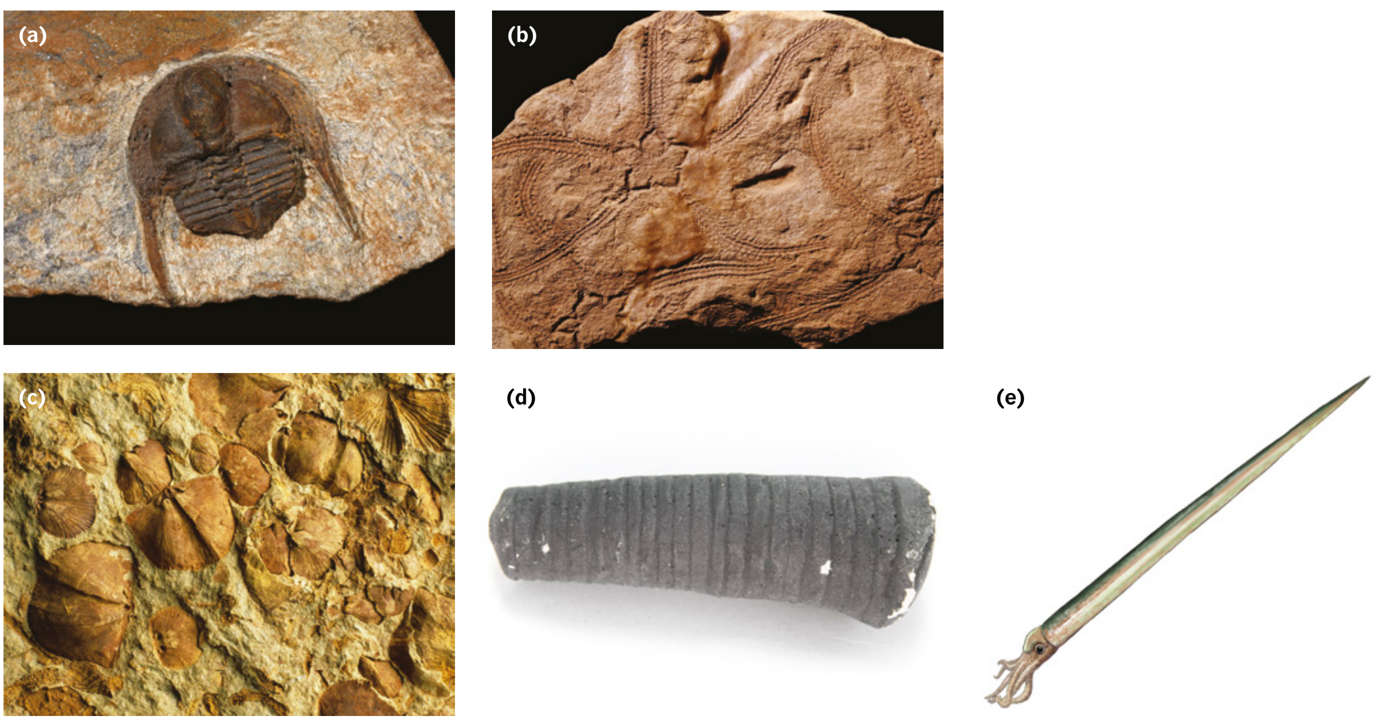


FIGURE 9.3.14 Animals from the Ordovician period: (a) trilobite, *Onnia* sp.; (b) sea stars, *Lapworthura miltoni*; (c) brachiopods, *Dalmanella* sp. and *Orthis* sp. (larger shells), and cephalopods; (d) nautiloid fossil and (e) illustration of a nautiloid

Silurian period (443.8–419.2 mya): the first life on land

After the Ordovician ice age, the Silurian rebounded to a long and relatively stable warm period. The relative oxygen levels were low compared to today, but the carbon dioxide was high.

The earliest evidence of life on land is from terrestrial rocks of the Silurian period. The first known air-breathing animals were arthropods. Millipedes, centipedes and the earliest arachnids also first appeared during the Silurian. The oldest known land plants date from the late Silurian. These were small, spore-bearing, vascular plants such as *Cooksonia* (Figure 9.3.16). *Cooksonia* had an aerial stem but lacked roots and leaves. It had xylem and phloem tissue to transport water and nutrients. It may be that non-vascular plants such as liverworts and mosses evolved on land earlier, but there is no definitive evidence of them until much later. Terrestrial fungi are also recorded as hyphae and spores from the Silurian.

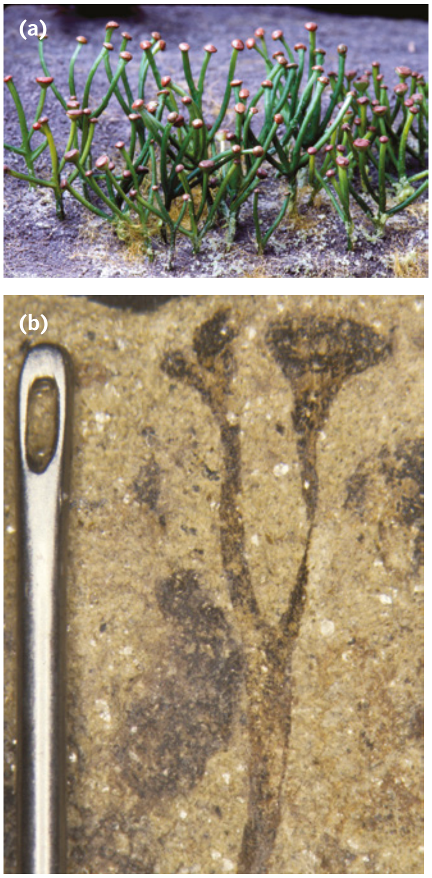


FIGURE 9.3.16 *Cooksonia*, named after the Australian palaeobotanist Isabel Cookson, is probably the earliest known vascular plant. (a) Model of Cooksonia from the Smithsonian National Museum of Natural History exhibit hall. (b) *Cooksonia* fossil next to a sewing needle for size comparison

Devonian period (419.2–358.9 mya): the first land vertebrates

The emergence of land-based plants and animals resulted in organic matter being deposited into the barren soils, promoting further colonisation of the land.

The vegetation of the Devonian period would have been only a few centimetres tall and spread by spores. The Devonian period is often referred to as the 'age of fishes' due to the diversification of this group. Jawed fishes evolved in the sea, along with armoured placoderms, ray-finned and lobe-finned fishes and early sharks (Figure 9.3.17).

One group of fleshy-finned Devonian fishes developed such sturdy fins that they were able to support their weight at the edge of the water. These animals would give rise to the first terrestrial vertebrates, the **tetrapods** (meaning four-footed) (Figure 9.3.18). The earliest tetrapods included amphibians.

FIGURE 9.3.17 Illustration of *Dunkleosteus*, a member of the class Placodermi. Placoderm fishes were distinguished by having heavily armoured heads and a scaleless body.

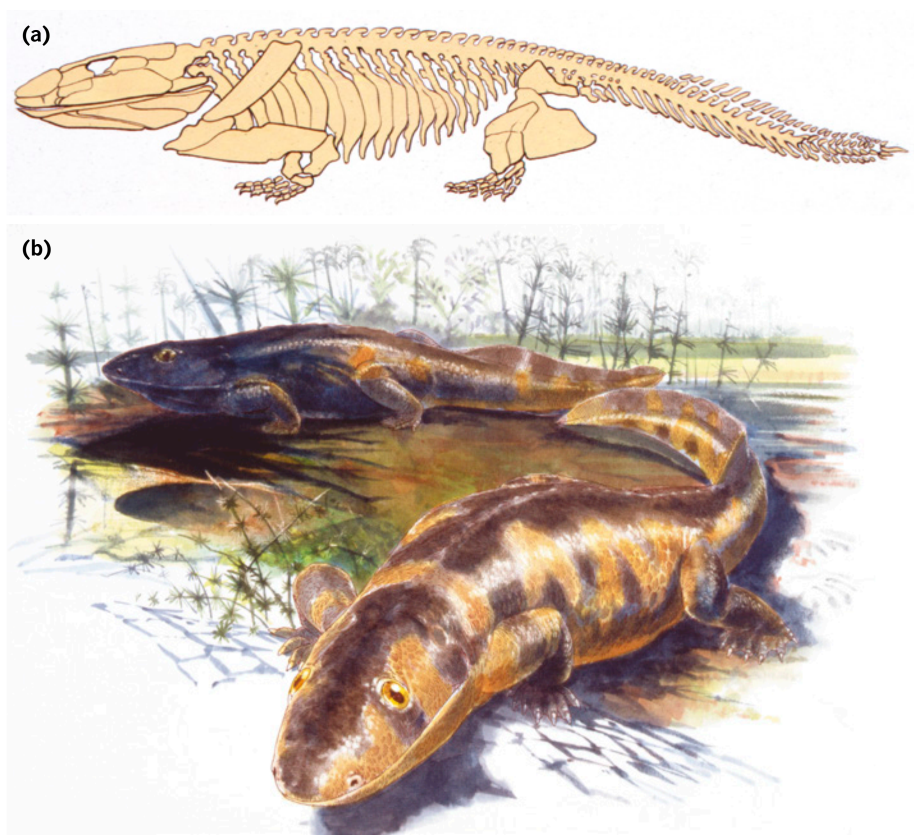


FIGURE 9.3.18 (a) Illustration of a skeleton of an early tetrapod, *Ichthyostega*, and (b) an illustration of how *Ichthyostega* might have looked

A tetrapod is a vertebrate (which includes amphibians, reptiles and mammals) with four limbs. Legless animals descended from four-limbed ancestors, such as snakes and whales, are also known as tetrapods.

Carboniferous period (358.9–298.9 mya): abundant forests

The Carboniferous period (the coal age) is characterised by abundant terrestrial plant life and huge arthropods. Spore-bearing plants developed tree-like forms, having woody stems, roots and leaves. Most of the land was covered in vast forests. New forest habitats influenced the diversification of animal species (Figure 9.3.19).

Since plants produce oxygen as a by-product of photosynthesis, the extent of forest coverage meant levels of atmospheric oxygen that have never been equalled (35% compared to today's 21%).

Arthropods' diffusion-based circulatory system can only oxygenate tissues over a certain distance, which is dependent on atmospheric oxygen concentration. At today's levels, this distance is only a few centimetres. The very high Carboniferous levels allowed a much greater distance, meaning that arthropods grew to enormous sizes up to 3 m.

A second effect of the forests was the build-up of dead woody material on the ground. Fungi of the Carboniferous had not yet evolved the ability to decompose lignin, the main structural component of wood. Thus, undecomposed wood accumulated in very deep layers, with the forest constantly growing over the top. Over geological time the buried carbon-rich material was compressed to form coal, now mined as a fossil fuel.

During the Carboniferous, the tetrapods were losing their amphibian-like bodies in favour of the long snouts and more agile limbs of early reptiles. The tetrapods were spending more time out of the water adapting to the terrestrial environment. An **amniotic** egg evolved and supported reproduction on land; scaly skin evolved and protected animals from dehydration.

Abundant plant growth also removes carbon dioxide from the atmosphere, so towards the end of the Carboniferous carbon dioxide levels fell and the period ended with another major ice age.

FIGURE 9.3.19 Artwork of a *Hylonomus* reptile and its prey, a giant dragonfly (*Meganeura monyi*), in a forest during the Carboniferous period

Permian period (298.9–252.2 mya): the greatest mass extinction

The Permian began in the grips of the severe ice age that started in the late Carboniferous. Also early in the Permian, the continents joined to form the supercontinent known as Pangaea (Figure 9.3.20).

Such joining is widely misunderstood to have been a unique event, but it was just the latest in a cycle of at least six earlier continental conjunctions and breakups. However, the formation and breakup of Pangaea affected the evolution of complex life far more than any other continental conjunction.

The formation of Pangaea had several major effects, the first being a tremendous reduction of coastal and continent-margin habitats. Second, coastal winds could only transport moisture a short distance inland from the coast. So the vast bulk of the inland region was a desert, far dryer than any on Earth today.

The rest of Earth's surface was a single huge ocean, which would have had a circular current around the supercontinent. Such conditions may have caused stagnation and de-oxygenation of the deep ocean, releasing large quantities of toxic hydrogen sulfide gas into the atmosphere.

Due to these and other factors, the Permian saw the greatest of all mass extinctions. Around 70% of land species and 90% of ocean species were wiped out. The Permian was the only mass extinction of arthropods, including the trilobites.

However, the dry conditions favoured the rise of reptiles. The Permian was also the time of mammal-like reptiles, including sailback species such as *Dimetrodon* (Figure 9.3.21).

FIGURE 9.3.20 The Pangaea supercontinent

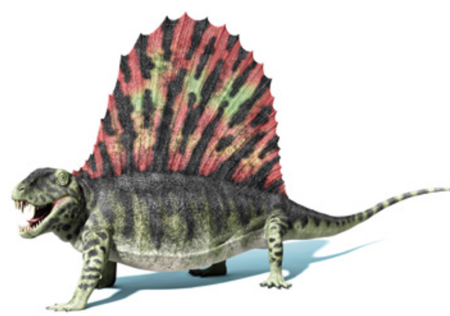


FIGURE 9.3.21 *Dimetrodon,* a mammal-like reptile, was the dominant land predator during the early Permian period, long before the dinosaurs.

THE MESOZOIC ERA: THE AGE OF THE DINOSAURS

FIGURE 9.3.22 Artwork of animals that existed in the Triassic period

FIGURE 9.3.23 Evidence of the first mammals is the genus *Morganucodon*, a 10 cm long weasel-like animal whose fossilised remains were first found in caves in Wales and around Bristol in the United Kingdom.

During the Mesozoic era, Earth gradually rebounded from the toll of the Permian. Pangaea started breaking apart during the Triassic period in the early Mesozoic. By the Jurassic period of the mid-Mesozoic, the breakup had led to two large continents, **Laurasia** and **Gondwana**. During the final period of the Mesozoic, the Cretaceous, each of these further broke up into somewhat familiar continents. During the Mesozoic, the world also started greening again, and the climate became less arid. Such changes provided new opportunities for animals and plants. Life diversified rapidly and some organisms grew enormous.

Triassic period (252.2–201.3 mya): the first mammals

The early Triassic was still quite dry. As Pangaea started breaking up during the mid-Triassic, warmer and more humid conditions returned. The change favoured seed plants, such as cycads and gingko trees, and also ferns. These groups are generally tough and difficult to eat so herbivores grew not only in number, but in size as well (Figure 9.3.22).

The period saw the proliferation of reptiles and their relatives. Mammal-like therapsids gave rise to the true mammals in the late Triassic. The early mammals were small, insectivorous, nocturnal, hairy and warm-blooded (**endothermic**) (Figure 9.3.23). The Triassic also saw the emergence of ichthyosaurs and other marine reptiles, plus the archosaurs: a huge and very important family that included pterosaurs, crocodilians and dinosaurs. Dinosaurs remained small during the Triassic.

Before, during and for a while after Pangaea's breakup, the land remained heavily de-vegetated. This affected the atmospheric oxygen content, which was 16% compared to today's 21%. In response the early dinosaurs evolved an efficient respiration system involving air-sacs and one-way lungs (Figure 9.3.24). This allowed them to maintain an endothermic, high-energy metabolism in a relatively low-oxygen environment such as birds have today.

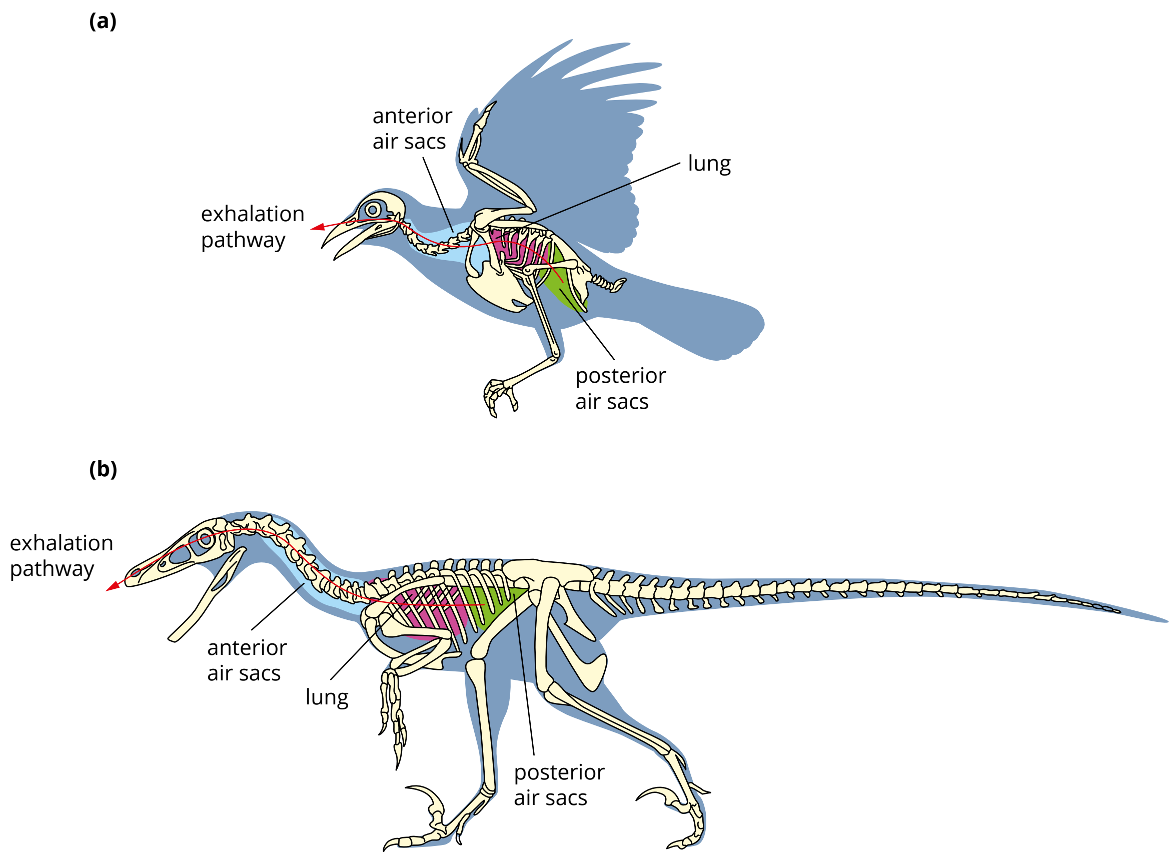


FIGURE 9.3.24 (a) Air-sacs in birds and (b) the identical structures in dinosaurs

The end of the Triassic saw another mass extinction, possibly related to the volcanism that broke up Pangaea. The extinction event affected the oceans more than the land, yet also cleared out major families of archosaurs, certain true reptiles, large amphibians and the last of the mammal-like reptiles. Dinosaurs were poised to take over.

Jurassic period (201.3–145 mya): the age of the dinosaurs

The early Jurassic saw the completion of the Pangaea breakup that had started during the Triassic. Pangaea broke up into two landmasses: Gondwana in the south and Laurasia in the north, separating northern and southern flora and fauna. That meant a greater amount of coastline, milder and more humid conditions and a re-vegetation of the land. Widespread return of forests raised atmospheric oxygen levels while carbon dioxide levels remained high, making the Jurassic mostly tropical or subtropical.

The period saw the arrival of the non-egg-laying mammals, and the first modern lizards.

The Jurassic is most famous for being the heyday of the dinosaurs. Although initially bipedal sauropods appeared late in the Triassic, the family reached its most impressive sizes during the Jurassic (Figure 9.3.25). The sauropods remain the most successful vertebrate group of all time.

FIGURE 9.3.25 Brachiosaurus, an iconic sauropod dinosaur from the Jurassic

Birds also first appeared during the Jurassic. While it is often implied that birds were separate from dinosaurs, they were then (and still are) a subgroup of reptiles. The oldest bird fossil from this period, *Archaeopteryx* (~150 mya), was simply a feathered dinosaur and otherwise indistinguishable from other **therapods** of the time (Figure 9.3.26). Feathers probably evolved first for insulation, and were later used for flight. Birds today retain all characteristic dinosaur features. Today we refer to dinosaurs as non-avian dinosaurs.

Cretaceous period (145–66 mya): the first flowering plants

Atmospheric carbon dioxide began lower in the Cretaceous than in the Jurassic. That meant a cooler climate, with frequent snow in high latitudes. However, carbon dioxide levels rose mid-period due to prolonged volcanic eruption, and soon the climate warmed up again. Laurasia had fully broken up during the Jurassic, and during the Cretaceous period Gondwana was still breaking up. High sea levels compared to today meant that about one-third of present-day lands were submerged, so shallow inland seas were common.

FIGURE 9.3.26 (a) Archaeopteryx fossil; the bones are surrounded by feathers (rippled areas), the head is at centre left. (b) Photographic reconstruction of *Archaeopteryx*

Dinosaurs reached their peak diversity. The first true placental mammals and marsupials appeared, as did mosasaurs: a terrifying family of predatory marine reptiles. The first grasses also arose.

At the end of the Cretaceous period, about 65 million years ago, another mass extinction occurred. This time an asteroid crashed into Earth, causing tremendous ecological disruption. Most forms of dinosaurs—except birds—became extinct, as did 76% of all land and marine species.

The dawn of the flowering plants

The early Cretaceous environments were still dominated by ferns, seed ferns, cycads and conifers; but **angiosperms** (flowering plants) also developed about 135 million years ago. Angiosperms diversified rapidly, and by the end of the Cretaceous were by far the most diverse group of land-based plants. The first angiosperms co-evolved with thriving insect populations, which pollinated the flowers (Figure 9.3.27).

Angiosperms may have arisen in direct response to dinosaurs. The largest dinosaurs were herbivores that also travelled in large herds that caused great forest disturbance, such as the clearance of vegetation. Fast-reproducing angiosperms had a clear advantage in colonising the bare soil compared to other plant groups of the time. Angiosperms have since gone on to overwhelmingly dominate Earth's flora, now comprising around 90% of plant species.

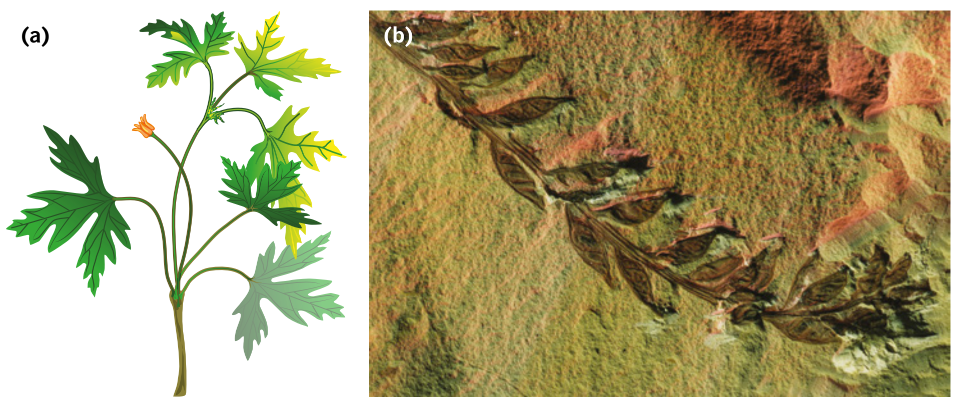


FIGURE 9.3.27 Earliest flowering plants from the Cretaceous period: (a) *Leefructus mirus* and (b) fossil of *Archaefructus* sp.

BIOFILE CCT

The K–Pg boundary

Originally known as the K–T boundary, marking the end of the Cretaceous period and beginning of the Tertiary period of the Cenozoic era, the event has been renamed the Cretaceous–Palaeogene boundary or K–Pg boundary.

This point in time is considered significant due to an extinction event that saw the end of the dinosaurs and many other life forms, and has been dated by a section of rock in El Kef, Tunisia. This section of rock highlights the moment an asteroid hit the Yucatan Peninsula (in modern Mexico), causing the Chicxulub crater and massive ecological changes. It contains: mineralogical evidence of the asteroid, such as increased iridium content; environmental evidence, such as evidence of tsunamis with ocean sand being significant distances from oceans; and the last of many species being identified in the fossil record (Figure 9.3.28).

FIGURE 9.3.28 The K–T boundary, now called the K–Pg boundary. The white line, level with the hammer's handle, is iridium-rich boundary clay. Iridium is not normally found in Earth's crust, and came from a meteorite impact 65 million years ago that wiped out the dinosaurs as well as many other species.

BIOFILE CCT

Extinction of the dinosaurs and survival of birds

The Cretaceous period ended suddenly. A 10–20 km asteroid, travelling at between 16–32 km per second, smashed into Earth. The impact released energy equivalent to perhaps a hundred million hydrogen bombs (Figure 9.3.29).

The immediate consequences were huge tsunamis, a shockwave and a nearly simultaneous fireball that travelled completely around Earth. The fireball incinerated nearly all forests within hours. A large proportion of animals would have perished on that first day.

The impact also released billions of tons of rocky debris into the high atmosphere and into orbit around Earth. The debris blocked out most sunlight for the next few months. This would have both cooled the planet substantially and prevented nearly all photosynthesis.

Most of the forests would have been destroyed, and the few that remained would not have been growing. Thus, any surviving herbivores would have quickly perished, followed soon by large carnivores. That explains why the dinosaurs died out almost immediately.

Yet not all did. One subfamily of dinosaurs survived: the birds. Their feathers gave them two key advantages over their non-feathered relatives. Feathers first evolved for warmth, plus they enable birds to fly. Thus, birds could have flown from one isolated food source to the next—animal carcasses or patches of surviving trees—while at the same time enduring the cold.

Mammals also survived relatively unscathed because some lived safely underground and were able to hibernate. All reptile orders other than the giant marine predators also survived. Being ectothermic, or cold-blooded, reptiles can easily last long periods without food, so they too survived through dormancy until food supplies returned.

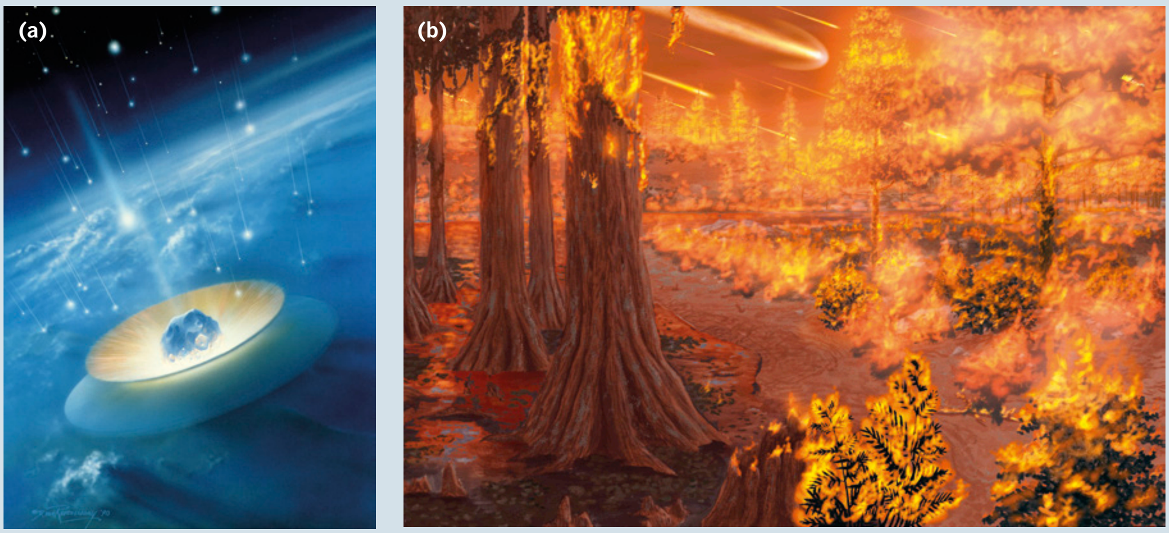


FIGURE 9.3.29 (a) Impact of an asteroid, estimated to have been 10–20 km across, seen from 100 km altitude. (b) A reconstruction of the aftermath of the asteroid impact

THE CENOZOIC ERA: THE RISE OF BIRDS AND MAMMALS

The Cenozoic era marked the shift towards the life forms we know today. Extinction of the Cretaceous giants (dinosaurs, pterosaurs and marine reptiles) enabled smaller species to quickly diversify and become larger. The era experienced an overall cooling and drying trend, culminating in a succession of severe ice ages caused in part by cyclic wobbles in the angle of Earth's axis of rotation.

Palaeogene period (66–23.03 mya): mammals diversify

The Palaeogene climate began with cooling and drying, followed by some exceptional warming periods. Both the carbon dioxide and oxygen concentrations were higher than today, but down from Mesozoic levels.

Mammals and birds took advantage of the niches left by the extinction of the dinosaurs. Birds became abundant and diverse, as new species of plant life evolved that served as shelter and food. Mammals thrived, diversifying to include most of the modern families. Mammals also took to the oceans for the first time. Some mammals became giants almost as large as dinosaurs. Early primates (prosimians) were common, but were eventually replaced by true monkeys and apes.

The continents continued moving towards their present positions. In particular India began its collision with Asia, which is still ongoing. The resulting changed ocean and atmospheric currents affected climates. In what is now Australia, rainforest vegetation was more widespread than it is today.

Neogene period (23.03–2.58 mya): the first hominins

The Neogene continued the cooling trend, which suited grasses over forests. Savannahs and steppes arose for the first time, favouring herds of grazing mammals.

Further major continental movement saw Australia fully separated from Antarctica, while South America and North America came together (Figure 9.3.30). Atmospheric gas concentrations were around their present levels, as were sea levels, and a series of ice ages started.

FIGURE 9.3.30 Illustration showing how the continents would have looked during the Neogene period

Flowering plants, birds and mammals had become recognisably modern. Animals across the globe included giant forms: the **megafauna**. In the Northern Hemisphere these included mammoths and other giant members of the elephant family, sabre-toothed tigers and ground sloths (Figure 9.3.31). Southern Hemisphere megafauna included huge lizards and marsupials.

The first **hominin** (human-like) fossils are 6–7 million years old, and the first species of the genus *Homo*, *Homo habilis*, dates to around 2.5 million years ago (Figure 9.3.32).

> Hominins include modern humans, all extinct members for the genus *Homo*, and our immediate ancestors (e.g. *Australopithecus*).

FIGURE 9.3.31 Illustration of a herd of mammoths (*Mammuthus columbi*) being attacked by sabre-tooth cats (*Smilodon fatalis*)

FIGURE 9.3.32 *Homo habilis* skull (left) and illustration of *Homo habilis* (right)

Quaternary period (2.58 mya–today): the expansion of modern humans

The Quaternary period is the time we are living in now and is the latest period of the Cenozoic era. It includes two epochs: the Pleistocene epoch (2.58–0.01 mya) and the Holocene epoch (0.01 mya–present). During the Quaternary period climates fluctuated from cold, dry glacial periods with low sea levels to warmer interglacial periods and higher sea levels. The Holocene epoch (up to today) is an interglacial period of unusually warm conditions relative to the era overall.

The climate started to become drier, which caused the rainforests to shrink in size. Plants and animals better suited to dry conditions started to spread. In Australia giant marsupials roamed, such as *Diprotodon*, *Procoptodon* and *Thylacoleo*. There were enormous goannas and large flightless birds.

Modern humans moved out of Africa, and the Neanderthals, *Homo neanderthalensis*, became extinct.

During glacial periods, when water was frozen in ice sheets, sea levels dropped and exposed land bridges for species to cross. Modern humans migrated via land bridges as well as using rafts or boats.

The Holocene epoch is by far the shortest geological time, only about 11 000 years. It did not include significant changes in species (until the period's end), but did include significant movement of species across continents. Among these species walked the first modern humans.

WS 3.6

BIOLOGY IN ACTION CCT IU

The Cradle of Humankind

A world heritage site that is located approximately 50 km north-west of Johannesburg, South Africa (Figure 9.3.34) is the world's greatest source of hominin fossils. It is also the source of some of the oldest, dating back as far as 3.5 million years.

The first major discovery of a hominin from this region was in 1924 when anatomist Raymond Dart found the skull of a juvenile primate among a box of fossil-bearing rocks. Now known as the Taung Child after the town where it was discovered, it was the first evidence of the hominin species *Australopithecus africanus*.

Since 1924, many other hominins including *Paranthropus robustus*, *Australopithecus sediba*, *Homo ergaster* and *Homo naledi* have been found in Africa. The discovery of *A. sediba* in 2010 is one of the most exciting. It is estimated to be nearly 2 million years old, and shares significant traits with the genus *Homo*, indicating their relationship.

The most recent find was in September 2015, when Lee Berger of the University of Witwatersrand, in collaboration with National Geographic, announced the discovery of *H. naledi*. Besides shedding light on the origins and diversity of our genus, *H. naledi* also appears to have intentionally placed bodies of its dead in a remote cave chamber, a behaviour previously thought limited to *Homo sapiens*.

FIGURE 9.3.34 Entrance to Maropeng Exhibition Centre, the Cradle of Humankind World Heritage site in Gauteng, South Africa

9.3 Review

SUMMARY

- The geological time scale is constructed via the relative order of rocks in a sedimentary rock sequence, fossils of ancient animals and plants within the rock, and direct radiometric dating of rocks.
- The largest subdivision of this time scale is an eon, which is subdivided into eras, then periods, then smaller subdivisions called epochs.
- The Archaean eon:
  - Life first appeared as prokaryotes (bacteria). These and archaea were Earth's sole inhabitants for more than 1500 million years.
- The Proterozoic eon:
  - Single-celled and multicellular eukaryotes (e.g. red algae) appeared.
  - The Ediacaran period includes the earliest evidence of multicellular animals (Ediacaran fauna), which were small, soft-bodied sea creatures resembling modern sea jellies and segmented worms.
- The Palaeozoic era:
  - Cambrian period: a dramatic increase in the number and complexity of marine life forms, including animals with exoskeletons.
  - Ordovician period: the first vertebrates, the jawless armoured fishes (ostracoderms), emerged.
  - Silurian period: the first known air-breathing animals were arthropods (millipedes and centipedes). The earliest arachnids also appeared. Small vascular plants colonised swampy land.
  - Devonian period: jawed marine fishes, armoured placoderms, ray-finned and lobe-finned fishes and early sharks evolved. One group of fishes developed sturdy weight-bearing fins that led to the evolution of tetrapods.
  - Carboniferous period: evolution of reptiles from amphibian-like ancestors. Formation of forests dominated by tree forms of spore-bearing vascular plants (e.g. lycophytes and sphenophytes).
  - Permian period: one supercontinent (Pangaea) formed, reptiles diversified and up to 90% of species were lost in a mass extinction event.
- The Mesozoic era:
  - Triassic period: reptiles were the dominant vertebrates. The archosaur reptiles had diversified into pterosaurs, crocodiles and the earliest dinosaurs. The earliest mammals emerged. Plants included cycads, ferns and Gingko-like trees.
  - Jurassic period: dinosaurs thrived and the warm, forested Earth led to the first gigantic sauropods and theropods. Mammals began to diversify. The oldest bird fossils are from the Jurassic.
  - Cretaceous period: dinosaur diversity peaked and small primitive marsupials and insectivores were abundant and widespread. Angiosperms (flowering plants) evolved.
- The Cenozoic era:
  - Palaeogene period: mammals evolved into many new species such as placentals and marsupials. Birds became abundant and primates evolved.
  - Neogene period: the first of the *Homo* species, *Homo habilis*, evolved.
  - Quaternary period: includes the Pleistocene and Holocene epochs (present day). Climates and sea levels changed from cold, dry glacial periods and low sea levels to warm, wetter interglacial periods and higher sea levels. Some animal species evolved into giants (megafauna) that later became extinct. Neanderthals (*Homo neanderthalensis*) and modern humans (*Homo sapiens*) evolved and co-existed until Neanderthals became extinct.

KEY QUESTIONS

1. **a** What information is used to construct the geological time scale?
   b What are the divisions in the geological time scale?
2. What are stromatolites?
3. Explain the defining features of life forms that can be used to distinguish between the Precambrian and the Palaeozoic era.
4. In which eon did multicellular animals and plants first appear?
5. **a** What were the first air-breathing animals on land?
   b Which group of organisms gave rise to reptiles?
   c When did the first mammals emerge?
6. **a** Based on known fossils, what are the earliest land (terrestrial) plants?
   b Name the period with the oldest land plants.
   c When did the first angiosperms appear?
7. State which natural event defines the boundary between the Cretaceous and Neogene periods.

Chapter review

KEY TERMS

adaptive radiation
adaptive value
allele
allele frequency
allopatric speciation
amniotic
amino acid
angiosperm
artificial selection
biodiversity
bottleneck effect
Cambrian explosion
coevolution
convergent evolution
cyanobacteria
Darwinism
divergent evolution
ecological niche
endemic
endosymbiotic theory
endothermic
eon
epoch
era
evolution
fertilisation
fitness
fossil record
founder effect
gamete
gene flow
gene pool
genetic drift
genetic variation
genotype
geological time scale
genus
Gondwana
heredity
hominin
hybrid
hybrid inviability
inbreeding
instant speciation
interbreed
lactation
Lamarckism
Laurasia
macroevolution
marsupial
mass extinction
megafauna
microevolution
mimicry
monotreme
natural selection
nondisjunction
Pangaea
parapatric speciation
parallel evolution
period
peripatric speciation
phenotype
placental
plate tectonics
polyploidy
postzygotic isolating mechanism
prezygotic isolating mechanism
punctuated equilibrium
radiometric dating
reproductive isolation
sexual selection
speciation
species
stratum (pl. strata)
stromatolite
sympatric speciation
tetrapod
therapod
transitional series
viable offspring
zygote

REVIEW QUESTIONS

1 Distinguish between Darwinian and Lamarckian theories of evolution.

2 Why do some organisms remain unchanged for great periods of time?

3 What is a mass extinction? Give examples of natural events that caused mass extinctions.

4 Why do species become extinct?

5 Explain the reason for the high rate of endemic species in Tasmania.

6 The long-nosed bat (*Leptonycteris yerbabuenae*) lives in areas near the border of Texas and Mexico. Its main food source is nectar and pollen produced by agave plants (*Agave parryi*). The bats have specialised feeding structures that allow them to reach the nectar (see image to the right). As they eat the nectar the bats become covered in pollen, which they then transfer to another agave plant thereby pollinating it. Many of these plants not only have flowers that are especially shaped for the feeding structures of the bats but they also flower at night when the bats are most active.

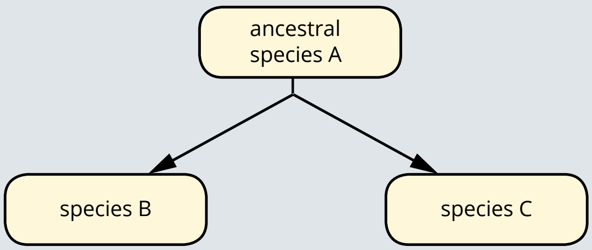
The relationship between the agave plant and the bats has occurred as a result of:

A convergent evolution
B divergent evolution
C parallel evolution
D coevolution

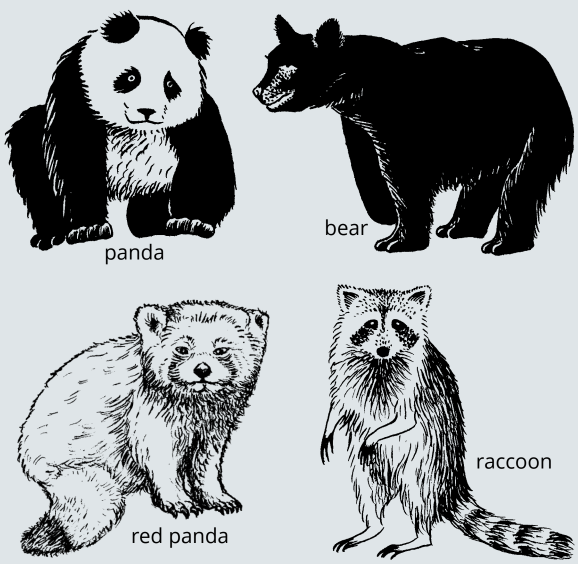
7 Which of the following is/are the source of new genetic material? More than one answer may be correct.

A gene flow
B natural selection
C genetic drift
D mutation

8 Consider the simple model of speciation illustrated below.
  a Use your understanding of variation, isolating mechanisms and natural selection to explain how an ancestral species might evolve into two new species.
  b What main criterion is applied to determine whether organisms belong to the same species or not?
  c Propose a mechanism that maintains reproductive isolation between two different but related species of:
    i song birds
    ii eucalypts in a stand of trees in a forest.



9 The red or lesser panda (*Ailurus fulgens*) was once thought to be closely related to the giant panda (*Ailuropoda melanoleuca*), both species occurring in China. Although members of the order Carnivora, both animals eat bamboo. However, genetic comparison has shown that red pandas are more closely related to racoons and giant pandas are related to bears.



  a Suggest reasons for the traditional view that the red and giant pandas were related.
  b Identify whether the similarity of each of the following pairs of animals is a result of divergent or convergent evolution.
    i red panda and giant panda
    ii red panda and raccoon

10 Treecreepers are a group of birds native to New Guinea and Australia. Currently seven species, divided into two genera (*Cormobates* and *Climacteris*), have been described. These small birds are insectivorous. They forage for food on trees, feeding on insects living on or under the bark. This feeding habit gives the group its name.
  a Tree creepers are a forest and woodland bird. In Australia, populations can become separated by areas of desert. There are two species of *Cormobates*: *Cormobates leucophaea* (white-throated treecreeper) shown in Figure (a), which is currently found in both northern Australia and New Guinea, and *Cormobates placens* (Papuan treecreeper), which is confined to New Guinea.
    i Using the theory of evolution by natural selection, deduce how these two species could have evolved.
    ii What kind of evolution is involved?

  b There are also treecreepers in Europe, such as the Eurasian treecreeper (*Certhia familiaris*) shown in Figure (b). These birds look very similar to the Australian and New Guinean varieties and occupy the same niche. The European and Australasian treecreepers all belong to the order Passeriformes but within that order they are as distantly related as it is possible to be and still be in the same order.
    i Discuss how the European and Australasian treecreepers have come to look and behave so similarly.
    ii What is the name given to this type of evolution?
    iii Identify the mechanism for this evolutionary process.

11 Natural selection acting over time on a population of wild mung beans is likely to result in which of the following?

A a change in the relative frequencies of alleles
B mutations
C extinction
D genetic drift

12 What mechanism is likely to maintain reproductive isolation between two different but related species of frogs living in the same marsh?

A The frogs breed at different times of the year.
B The mating calls of the frogs are different and they only respond to their own call.
C Hybrids between the two frogs are sterile.
D All of the above are possible mechanisms.

13 The coyote (*Canis latrans*) and the grey wolf (*Canis lupus*) are closely related species and both have a diploid chromosome number of 78. The ranges of the two animals overlap. Hybrids have been identified in the wild. The hybrids seem to express more coyote genes than wolf genes, but are bigger and more able to withstand harsh conditions than pure-breed coyotes. Breeding experiments in which female coyotes were crossed with male wolves resulted in viable offspring but showed reduced fertility, with two out of three pregnancies failing. Hybrids, however, are able to reproduce with a lower success rate than pure breeds of either species.

Genetic studies have shown that the eastern coyote population is almost certainly the result of such matings in the past (more than 200 years ago). Which of the following is the best description of this situation?

A prezygotic isolation
B reduced hybrid viability
C hybrid sterility
D hybrid inviability

14 Consider the following four populations.

1 a large population experiencing large environmental changes
2 a small population experiencing large environmental changes
3 a large population in a stable environment
4 a small population in a stable environment

The rate of evolution from fastest to slowest in these populations could be expected to be:

A 3, 4, 1, 2
B 4, 2, 3, 1
C 1, 2, 3, 4
D 2, 1, 4, 3

15 **a** Recent studies of human and chimpanzee genomes have shown that populations of chimpanzees living near each other show greater genetic variation than human populations spread on different continents. Explain how this supports the hypothesis that the human population experienced a genetic bottleneck about 75 000 years ago when Mt Toba, a supervolcano in Sumatra, erupted.

b The genetic bottleneck is one hypothesis to explain the lack of human genetic variation. Another is that human diversity is low because we are the result of a series of founder populations. Explain why the descendants of founder populations have low diversity.

16 Rabbit calicivirus is a disease that was introduced into the Australian mainland in 1995 and Tasmania in 1997. The purpose of the introduction was to reduce the number of wild rabbits as they had reached plague levels and were causing land degradation. Initially, millions of rabbits died but by 2005 numbers were again rising as the rabbits developed resistance to the virus.

a Explain how resistance to calicivirus has developed. Ensure you refer to allele frequencies in your answer.

b Is the action of calicivirus on the Australian rabbit population an example of artificial or natural selection? Explain your reasoning.

c The Department of Primary Industries introduced a new and more virulent strain of calicivirus into Tasmania in March 2017. Explain if this is likely to be more successful in eradicating the rabbit from Tasmania.

17 Speciation can take tens to hundreds of thousands of years or it can happen very rapidly. An example of rapid speciation has occurred over the last 150 years in the USA. In the early 1900s three species of related wild flowers from the genus *Tragopogon* (*T. dubius*, *T. pratensis* and *T. porrifolius*) were introduced into the USA from Europe. In all three species their haploid chromosome number is $n = 12$. Initially these were separate populations, but eventually their ranges began to overlap and interactions between the individuals of different species occurred and hybrids were formed. These hybrids were sterile.

Explain why the hybrids were sterile.

18 One iconic Australian animal is the corroboree frog. There are two species: the southern corroboree frog (*Pseudophryne corroboree*) and the northern corroboree frog (*Pseudophryne pengilleyi*), both pictured below. They are quite small, measuring between 2.5 and 3 cm in length. The two species are closely related but still have distinct differences in colour, mating calls and skin chemistry. Both breed in damp marshy areas. Both species are seriously endangered.

As seen in the map below, the geographic ranges of the northern and southern corroboree frogs do not overlap.

a The two species have a recent common ancestor. Describe the processes that could have resulted in the formation of the two species of frog.

b The northern corroboree frog is divided into two genetically distinct populations, both of which contain few individuals. How might this affect the viability of these populations over the next decade?

c There is a captive breeding program at Taronga Zoo for the northern corroboree frog. It has been suggested that individuals from the two separate populations of the northern corroboree frog should be interbred. How would this help to increase the chances of the survival of this species?

19 Even though not all dogs can interbreed with each other, currently all domestic dogs are considered to be a single species, *Canis lupus familiaris*. This is because alleles can be spread between different breeds by dogs of mixed breed.

If a situation were to occur in which all breeds of dog died out (perhaps due to a disease) except for Jack Russell terriers and Irish wolf hounds (pictured below), should the two breeds still be considered the same species? Justify your position.

20 The history of the Earth is divided into eons, eras, periods and epochs.

a Which of these spans the shortest length of time?

b The smallest subdivisions of the geological time scale are only seen during the Cenozoic. Explain why.

c Organise the following events from most ancient to most modern.

- adaptive radiation of mammals
- dinosaurs become extinct
- *Homo sapiens* evolve
- angiosperms evolve
- the great extinction event (up to 90% of all species died out)
- first algae

21 Which of the following statements is it true to say of the diagram below of the history of Earth?

Phanerozoic												Proterozoic	Archaean	Hadean
Cenozoic			Mesozoic			Palaeozoic								
Quaternary	Neogene	Palaeogene	Cretaceous	Jurassic	Triassic	Permian	Carboniferous	Devonian	Silurian	Ordovician	Cambrian			

↑ Q

↑ H

A Point Q occurred 2.6 million years ago and Point H occurred 4000 million years ago.

B Point Q occurred 100 000 years ago and Point H occurred 4000 million years ago.

C Point Q occurred 26 million years ago and Point H occurred 4500 million years ago.

D Point Q occurred 2.6 million years ago and Point H occurred 4500 million years ago.

22 Stromatolites are found today in the shallow, warm waters of Shark Bay in Western Australia. Which of the following statements is false?

A A stromatolite is a type of domed rock formed by layers of growth of cyanobacteria that trap sediments.

B A stromatolite is an accumulation of primitive eukaryotic marine fossils.

C Ancient stromatolites are fossil evidence of the early evolution of prokaryotes.

D Stromatolites represent evidence of early prokaryotic organisms.

23 The coelacanth (*Latimeria chalumnae*) is sometimes described as a living fossil. Coelacanths first appear in the fossil record 400 million years ago. Until 1938 they were thought to have become extinct around 65 million years ago in the K–Pg extinction event. Which of the following is most likely to explain the longevity of the coelacanth?

A They did not compete with each other for food.

B They did not have any predators.

C They produced many offspring.

D Their environment was stable and they were well adapted to it.

24 Ammonites are an extinct group of molluscs. The last known species died out in the K–Pg event. Ammonites were cephalopods like octopus and squid but their closest living relative is the nautilus (Figure (a)). Figure (b) shows the fossils of two different species of ammonite, the *Asteroceras confusum* (large ammonite) and *Promicroceras planicosta* (small ammonite).

a **i** What was the K–Pg event?

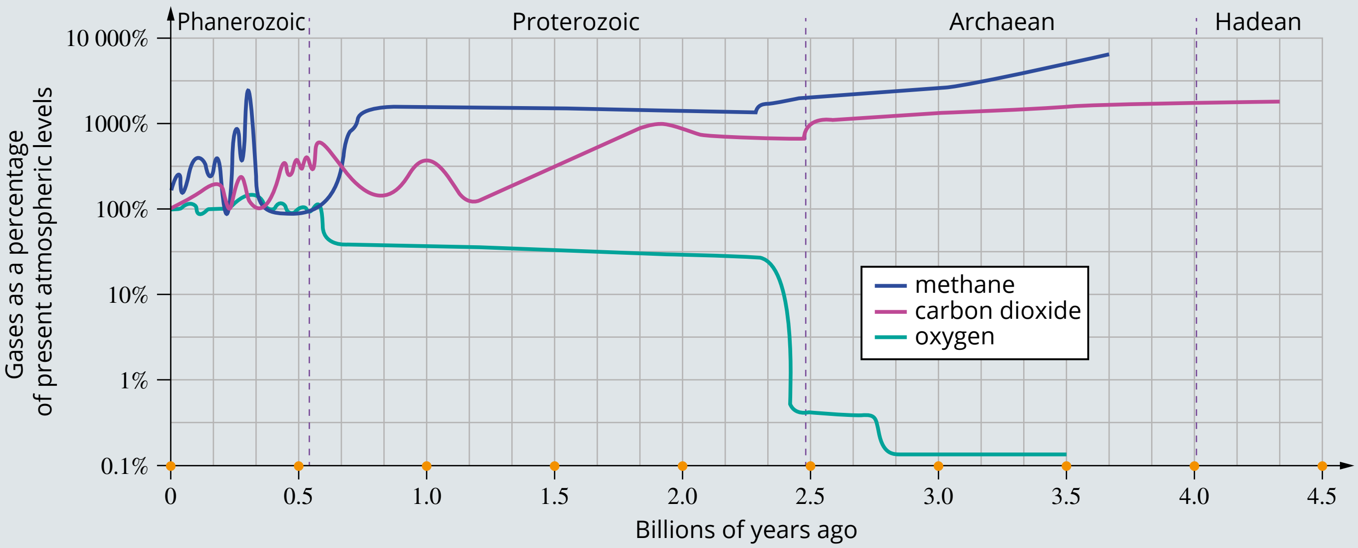
ii What is one suggested cause of this event?

b Other than size, how might palaeontologists have determined that these two ammonites are different species?

c Why might size be a poor feature to use to determine that two individuals are from different species?

25 Concentrations of atmospheric gases have changed over geological time. One view of these changes is represented on the graph below, which shows concentration of atmospheric methane, carbon dioxide and oxygen over time. Although there is consensus over general trends in atmospheric changes, there is still debate around some of the finer details.

Concentrations of methane, carbon dioxide and oxygen in comparison to present levels



a Why is there a lack of consensus about the details of atmospheric conditions in the early Earth?

b The graph uses a logarithmic scale so care needs to be taken with reading values.
The table below shows the concentration of the three gases in the atmosphere today.

Gas	Concentration in parts per million
methane	1.8
carbon dioxide	398
oxygen	210 000

Use the graph to determine the oxygen concentration (in parts per million) 3 billion years ago.

c What evidence can be seen in the graph that supports the theory that photosynthetic organisms arose approximately 2.8 billion years ago?

d The Great Oxygenation Event saw a rapid rise in oxygen levels to levels approaching modern values.

i When did this occur?

ii Which organisms were responsible for the Great Oxygenation Event?

26 After completing the Biology Inquiry on page 382, reflect on the inquiry question: What is the relationship between evolution and biodiversity? Define the term 'evolutionary success' and propose why this term does or does not reflect the true relationship between evolution and biodiversity.

CHAPTER 10

Evolution—the evidence

This chapter examines the evidence supporting the theory of evolution by natural selection, including evidence from fossils, biogeography, comparative anatomy, comparative embryology and biochemistry. Evidence of modern evolutionary change will also be examined, including the cane toad and antibiotic-resistant strains of bacteria.

Content

INQUIRY QUESTION

What is the evidence that supports the theory of evolution by natural selection?

By the end of this chapter you will be able to:

- investigate, using secondary sources, evidence in support of Darwin and Wallace's theory of evolution by natural selection, including but not limited to: ICT L
  - biochemical evidence, comparative anatomy, comparative embryology and biogeography (ACSBL089) ICT L
  - techniques used to date fossils and the evidence produced ICT L
- explain modern-day examples that demonstrate evolutionary change, for example: ICT L
  - the cane toad
  - antibiotic-resistant strains of bacteria

10.1 Evidence for evolution by natural selection

BIOLOGY INQUIRY CCT ICT WE

The case for evolution: flightless birds

What is the evidence that supports the theory of evolution by natural selection?

COLLECT THIS…

- coloured pencils
- outline map of the world
- tablet or computer to access the internet

DO THIS…

1 Working in pairs, use the internet to find out the distribution of penguin species around the world.
2 Shade the map of the world to represent where penguins live. Use one colour to represent all penguin species.
3 Looking at your map, reflect on and discuss with your partner the evolutionary significance of the distribution of the penguins.
4 Write a short summary of your discussion in point form.
5 Penguins, along with emus, ostriches, cassowaries, kiwis, rheas, moas and elephant birds, are flightless birds. Moas and elephant birds are extinct. As a pair, select another group of flightless birds (other than penguins).
6 Reflecting on your summary from step 4, shade the map where you expect your flightless bird group to live (or have lived if extinct). Use a different colour pencil to represent the distribution of this group.
7 Write a short summary explaining the distribution you predicted, justifying how the distribution relates to the evolutionary history of flightless birds.
8 Use the internet to check how accurate you were.
9 Use a different colour pencil to shade the actual distribution of your flightless bird group.

RECORD THIS…

Describe the patterns you notice in the distribution of flightless birds.

Present your map to the class and compare the distributions of different flightless bird groups.

REFLECT ON THIS…

Explain the distribution of penguins and other flightless birds in the context of biogeography.

How does this help us to reconstruct evolutionary records without fossils?

What is the evidence that supports the theory of evolution by natural selection?

Evolution is the process of biological change over time. These changes give rise to variation in life forms, known as biodiversity.

Evolution is a process of change. The modern theory of evolution states that all living organisms share a common origin that dates back to around 3800 million years ago. In Chapter 9 you learnt that the environment and its inhabitants have changed dramatically since life began on Earth. The earliest organisms were bacteria and, over a long period of time, very different groups of organisms diverged from these early forms of life. Some groups became extinct, while others changed over time to become the types of organisms that we see today.

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In this section, you will learn about the evidence for biological change over time, including evidence from the fossil record, biogeography, comparative anatomy, comparative embryology and biochemical evidence such as **DNA sequences**.

FOSSILS AND PALAEONTOLOGY

Palaeontology involves the study of ancient life represented by **fossils**. Fossils are the preserved remains, impressions or traces of organisms found in ice (Figure 10.1.1), rocks, amber (fossilised tree sap) (Figure 10.1.2), coal deposits or soil. Preserved remains are usually hard structures that are not easily destroyed or are slow to decompose, such as bone, shell, wood, leaves, pollen and spores. The **fossil record** refers to the total number of fossils that have been discovered, providing evidence of the evolution of living organisms through geological time. Fossils tell palaeontologists about the kinds of organisms that lived in the past, what they looked like, and where and when they lived. This allows scientists to put a time scale on evolution.

FIGURE 10.1.1 Palaeontologists studying a female woolly mammoth (*Mammuthus primigenius*) calf that died approximately 40 000 years ago at the age of about 1 month. Woolly mammoths became extinct around 10 000 years ago.

Fossilisation process

Fossilisation is the preservation of the hardened remains or traces of organisms in rock formations.

The chances of an organism becoming fossilised after death are small. Soft-bodied organisms are unlikely to be preserved, because soft body parts decay readily or are subject to predation and scavenging. Fossilised parts of plants are commonly wood and leaves made up of cellulose and lignin, which does not decay readily, and spores and pollen, which are even more resistant to decay.

Fossilisation has a chance of occurring when an organism is buried by sediments. This reduces the chance of decay, due to lack of oxygen for decomposer microorganisms, and hides the organism from scavengers. When sediments of sand, silt or mud in a sea, lake or slow-flowing stream accumulate over the organism, the organism is preserved. The weight of many layers of sediments squeezes out the water between the particles of sand, silt or mud. As the deposit deepens, the temperature increases and soft sediments become solid rock, known as sedimentary rock. Examples of sedimentary rock are sandstone, siltstone, mudstone and shale (a mixture of clay and silt) (Figure 10.1.3).

FIGURE 10.1.2 A fossilised midge insect (family Chironomidae) embedded in amber. The insect is related to present-day non-biting midges and is approximately 40 million years old.

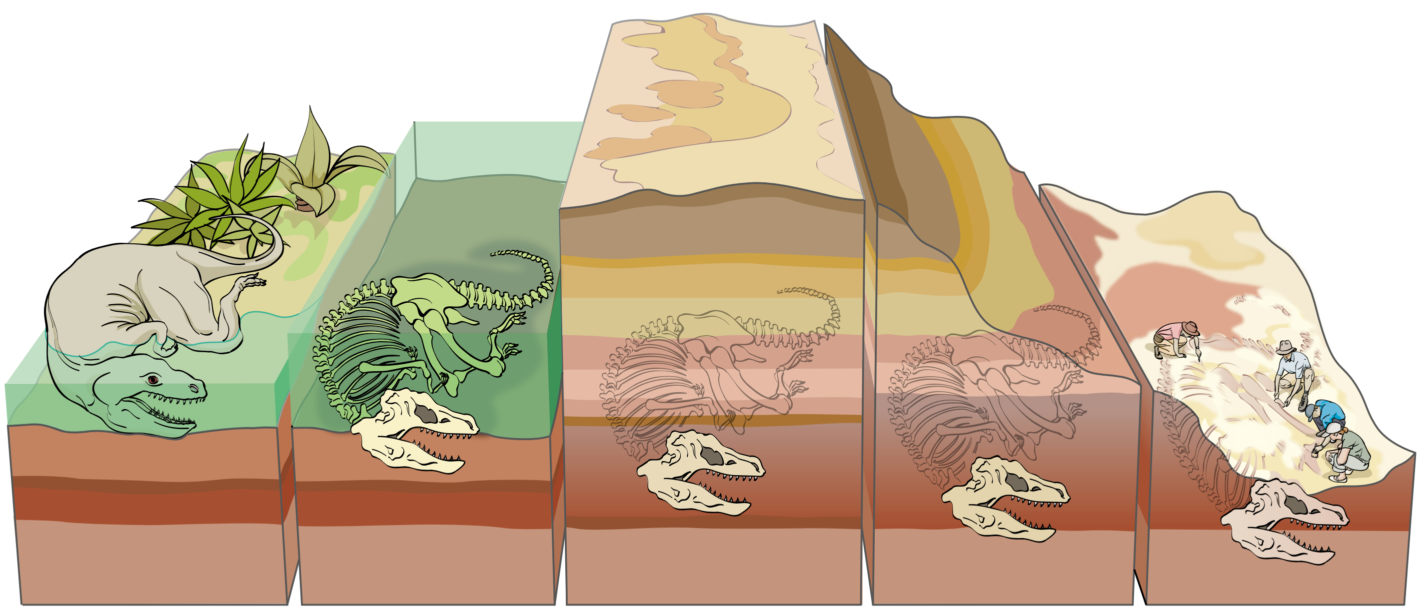


FIGURE 10.1.3 The sequence of events leading to the formation and subsequent discovery of a fossil. The organism dies (a) and is buried (b). Sediments accumulate and solidify to rock (c). Subsequent uplift, erosion and exposure (d) lead to its discovery (e).

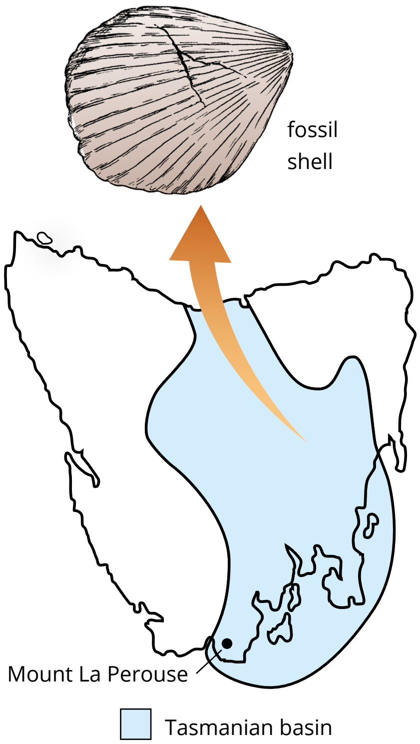


FIGURE 10.1.4 Fossil shells, fishes (including lungfish) and amphibians about 280 million years old have been found at Mount La Perouse in Tasmania.

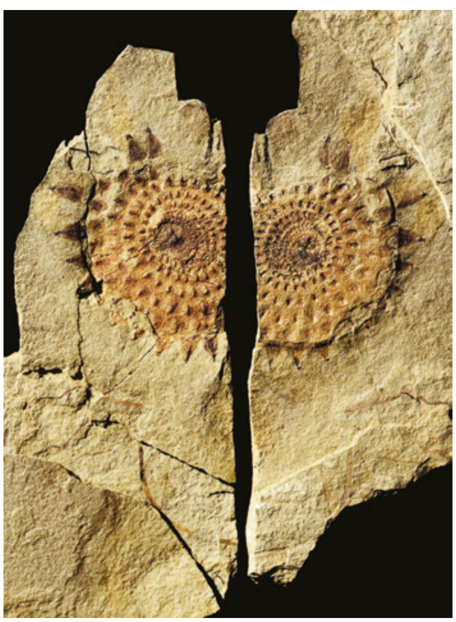


FIGURE 10.1.5 Impression fossil of *Equisetum* (horsetail plant). The sandstone block has split open to reveal a rare fossil imprint of a terminal bud from an *Equisetum* horsetail plant from the Triassic period.

Sediments accumulate in bodies of water such as seas, estuaries and lakes; hence, a large proportion of fossils are found where ancient bodies of water existed. Fossil shells formed in this way in Tasmania. In the Carboniferous and early Permian periods (about 280 million years ago) a marine gulf formed the Tasmanian Basin. The basin filled with mud and silt washed down from glaciated uplands. The sediments formed layers of mudstone, siltstone, sandstone and some limestone. The basin later became a larger plain, with lakes and freshwater streams that deposited other sediment layers. Fossil shells, fishes (including lungfish) and amphibians have been found in siltstone and sandstone at Mount La Perouse in Tasmania (Figure 10.1.4).

Organisms on land are less likely to be preserved than those that live in aquatic environments. For example, plants that grow along river banks or on the edge of swamps, where sediments can trap leaves, fruits and seeds, are more likely to be fossilised than plants that grow only on rocky outcrops. Delicate plant parts such as flowers are rarely fossilised, although some are preserved by being buried rapidly (e.g. by ash from an erupting volcano). For these reasons the fossil record is biased towards certain sorts and parts of organisms and certain environmental conditions, which then limits the available evidence of past life and our understanding of it.

Types of fossils

The four main types of fossils are impression fossils, mineralised fossils, trace fossils and mummified organisms.

Impression fossils

Impression fossils are left when the entire organism decays but the shape or impression of the external or internal surface remains (Figure 10.1.5). In some rocks such as limestone the fossils keep their three-dimensional shape, but in other rocks (e.g. shales) or in coal deposits that are physically compressed, fossils are flattened. Impression fossils include the internal surface of a shell, tree trunks and plant leaves. If the vacant space of the mould is later filled with foreign material, a three-dimensional 'sculpture' of the organism is formed; this is called a cast fossil.

Mineralised fossils

Mineralised fossils occur when minerals replace the spaces in structures of organisms such as bones. Minerals may eventually replace the entire organism, leaving a replica of the original fossil (e.g. petrified wood). This process is known as **mineralisation** or **petrification**. Minerals can include opal, pyrite and silica (Figure 10.1.6).

FIGURE 10.1.6 Examples of mineralised fossils. (a) Petrified wood from the Petrified Forest, Arizona, USA. This fossil is from the late Triassic, when the forest was rapidly buried under volcanic ash. (b) Rock containing a fossil of a *Phareodus* sp. fish from the Eocene epoch. (c) Coloured scanning electron micrograph of fossilised diatoms, single-celled planktonic algae. Diatoms have a wall of silica that provides protection and support, which is readily fossilised. These diatoms are from the Miocene epoch.

Trace fossils

Trace fossils (also called ichnofossils) are the preserved evidence of an animal's activity or behaviour, without containing parts of the organism. Impressions such as footprints are trace fossils, as are casts of burrows or even coprolites (fossilised faeces) (Figure 10.1.7).

Trace fossils of footprints are formed when an organism steps into soft mud. The impression is then covered with loose sand so that the footprint is filled. The sand in the footprint is eventually compacted into sandstone. Finally, when the rock is split open along the bedding surface, the original footprint is revealed (Figure 10.1.8).

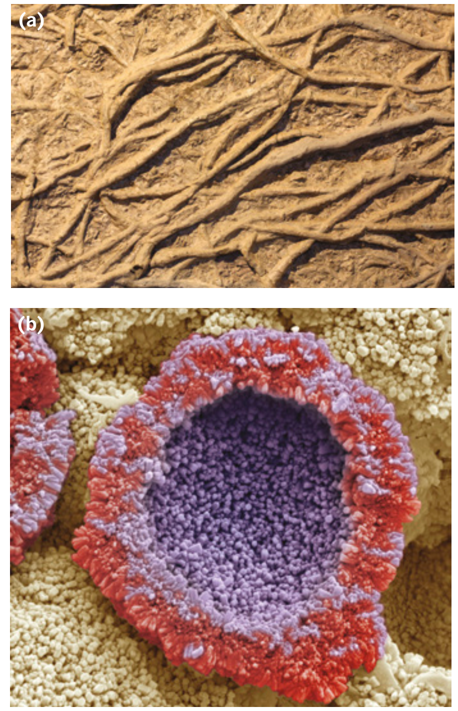


FIGURE 10.1.7 Examples of trace fossils. (a) Fossil worm burrows (*Arthrophycus* sp.) from the early Silurian. (b) Coloured scanning electron micrograph of a section through a coprolite from a dinosaur

FIGURE 10.1.8 Fossils appear when rock slowly forms around objects buried in mud. As the rock forms, the shape and anatomy of buried animals and plants can be preserved, including tracks such as these footprints.

Mummified organisms

Mummified organisms are those that have been trapped in a substance under conditions that reduce decay and so undergo little change. Examples include insects trapped in amber, leaves that still contain carbon dioxide (Figure 10.1.9) and animals frozen in ice or trapped in a peat bog (known as a 'bog body'). Mummified animals, including humans, can have hair and skin preserved in a dehydrated state, while limbs and occasionally entire bodies are preserved in peat bogs and tar pits (Figure 10.1.10).

FIGURE 10.1.9 This leaf from coal deposits in Anglesea, Victoria, is a mummified fossil and still contains carbon dioxide. It was preserved in layers of mud sandwiched between layers of coal.

FIGURE 10.1.10 Mummified body of Tollund Man, dated 220–40 BCE. This well-preserved body of an adult man was discovered in 1950 in a bog at Tollund Mose in Jutland, Denmark.

Dating fossils

The age of a fossil is almost as important as its physical details because it gives a time scale of evolution. The age of a fossil can be determined by **relative dating** or by **absolute dating** methods.

BIOFILE CCT

Dinosaur Cove

Dinosaur Cove, on the southern coast of Victoria, is famous for its fossil deposits. An ancient stream flowed through the site 106 million years ago, depositing soft sand and mud, which turned to rock. Palaeontologists have uncovered bones from small, bipedal dinosaurs that were trapped in these sediments and well-preserved tracks (footprints) of ancient birds. These tracks are estimated to be 105 million years old, making them Australia's oldest known bird tracks (Figure 10.1.11). At the time that these dinosaurs lived near the cove, Australia was further south and connected to Antarctica. Although not frigidly cold, winter was a long period of darkness. The hypsilophodontids had large optic lobes in their brains, meaning that they could probably see well in the dark.

FIGURE 10.1.11 Cretaceous bird tracks on a slab of sandstone found at Dinosaur Cove, southern Victoria, Australia

Relative dating

Relative dating is based on stratigraphy. **Stratigraphy** is the study of the relative positions of the rock strata (singular **stratum**), or layers, some of which contain fossils. The lowest stratum is the oldest and the upper strata are progressively younger. The age of a fossil is estimated relative to the known age of the layers of rock above and below the layer in which the fossil is found (Figure 10.1.12). For example, if a layer containing fossils lies below rock that is dated at 200 million years old, then the fossils must be at least that age or older. Relative dating can be difficult in areas where rock layers have been eroded, or where rocks have been buckled, moved or reburied, altering the original sequence of strata.

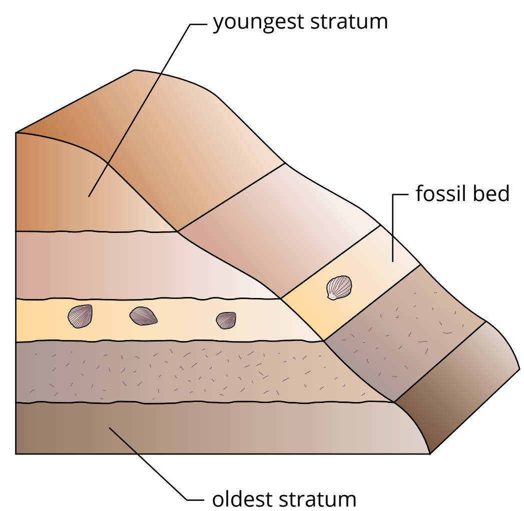


FIGURE 10.1.12 Relative dating assumes that rock strata (layers) are laid down in the order of the formation: the bottom stratum is the oldest, the top the youngest.

An **index fossil** (sometimes known as an indicator fossil) is a fossil used to define and identify geologic periods. Sometimes the only way to age a fossil bed is by using index fossils and stratigraphy. Index fossils are commonly found fossils from similar sites for which an absolute age has been determined. For example, in Europe the same type of ammonite (extinct mollusc) is found in different regions. A species of ammonite fossil is called an index fossil because it indicates that the rocks at each locality are of similar age (Figure 10.1.13).

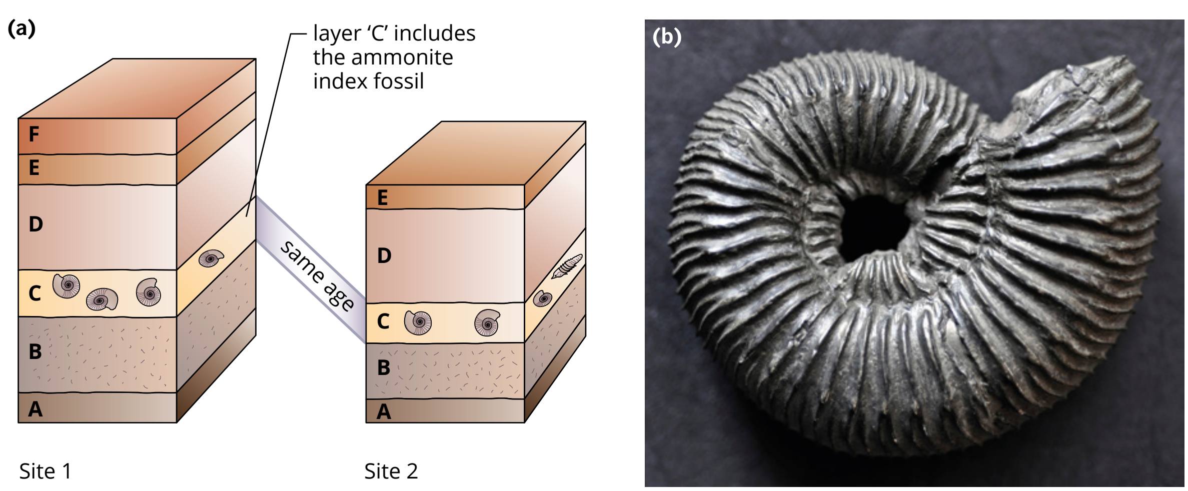


FIGURE 10.1.13 (a) Stratigraphic comparison of sites in different parts of the world provides evidence of the relative age of particular strata. The ammonite (mollusc) fossils of known age at site 1 are the same as at site 2, so the two strata are assumed to be the same age (even though site 1 has an additional, younger layer, F, at the top). The ammonite is an index fossil for the age of all the other fossils in the fossil layer at site 2. (b) Ammonites are an extinct group of marine molluscs. The hard shells of ammonites have fossilised well, making them important index fossils.

BIOFILE CCT

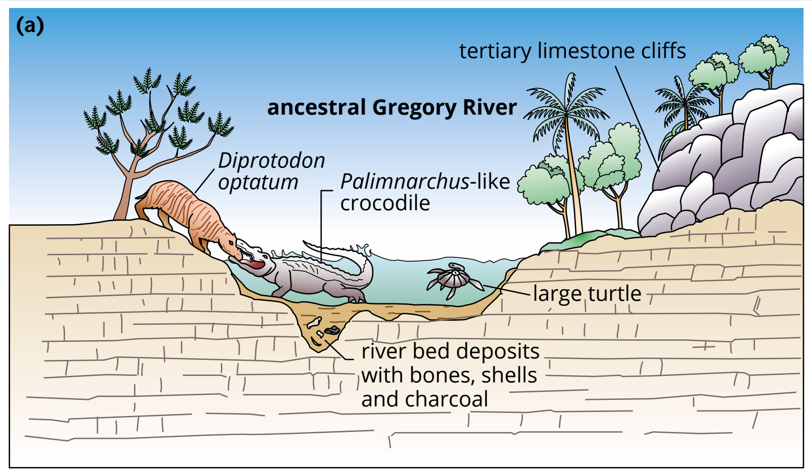
Fossil sites of inland Australia

Riversleigh in north-west Queensland

Riversleigh and the nearby Gregory River contain one of the great fossil sites in the world. Extinct animals are preserved in limestone of various ages, dating back more than 30 million years (Oligocene period). The fossils at this site reveal the story of ancient rainforest animals and plants that once lived in inland Australia. Fossil remains of the extinct marsupial *Diprotodon optatum* have been uncovered from the ancient bed of the Gregory River. These animals were probably killed by crocodiles as they came to drink from the river, and their bones accumulated as fossils in layers of sand and gravel (Figure 10.1.14). These particular fossils are approximately 1 million years old (from the late Pleistocene).

Koonwarra in Gippsland, Victoria

At Koonwarra in Gippsland, Victoria, scientists have uncovered a great diversity of organisms trapped in the bed of an ancient lake (Figure 10.1.15). The fossils are preserved in mudstone 115 million years old. Many of the fossils are fishes and the fossil site is named the 'Koonwarra Fish Beds'. One plant fossil is a leaf of *Ginkgo*. Today, the *Ginkgo* (*G. biloba*) is native to China, but trees of this genus were probably once widespread in the world, as shown by the 115 million-year-old fossil from Koonwarra.



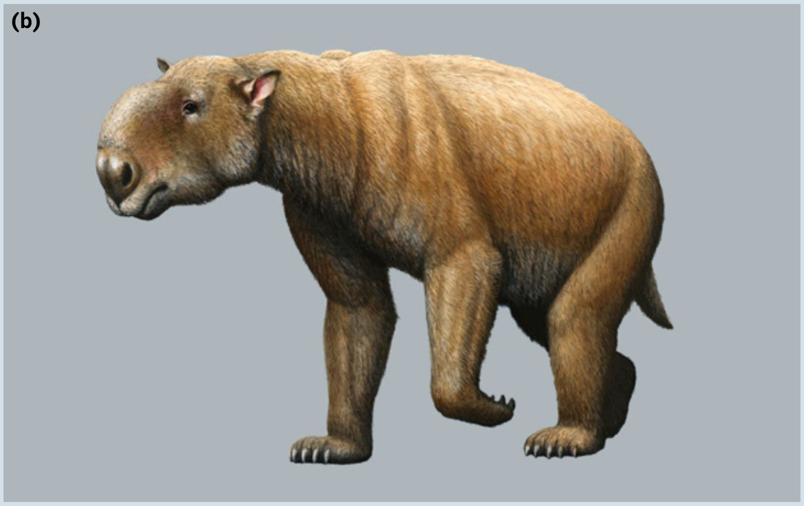


FIGURE 10.1.14 (a) Formation of fossils in the ancient Gregory River, about 1 million years ago. (b) Giant wombat, *Diprotodon optatum*

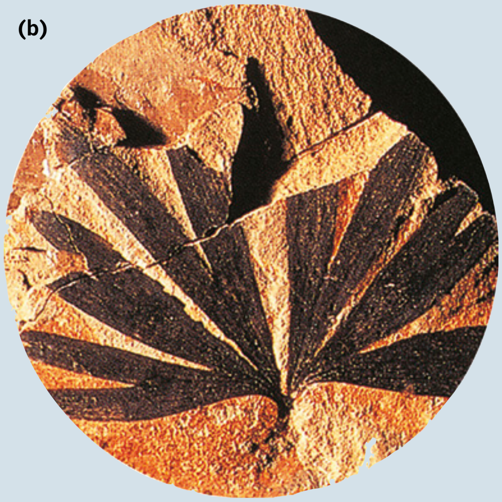


FIGURE 10.1.15 (a) Fossil fish and (b) Ginkgo leaves, 115 million years old, found at Koonwarra, Victoria

Absolute dating

Absolute dating provides a more precise estimate of age, although it does not mean that it provides an exact date. Radiometric dating, thermoluminescence and electron spin resonance are all methods of absolute dating that are used to determine the age of fossils.

- Radiometric dating is a quantitative technique used to determine the proportion of particular radioactive elements (**isotopes**) within rocks around fossils or sometimes within a fossil. Radioactive elements decay into different forms (e.g. uranium to lead, carbon to nitrogen) at rates that are constant for a particular element. The rate of decay of the element is independent of the nature of the rocks or the environmental conditions to which they are exposed, so they act as accurate clocks. The **half-life** of a radioactive element is the time taken for half the atoms of the element to decay, and can be used to calculate the age of the rock in which it is contained (Figure 10.1.16).
  - Carbon dating is a commonly used method of radiometric dating. It can only be used to determine the age of artefacts and fossils that were once living (i.e. contain carbon) and are younger than 50 000 years old. This is because the amount of carbon is too small to detect after this time. You will learn more about radiometric dating in Chapter 12.

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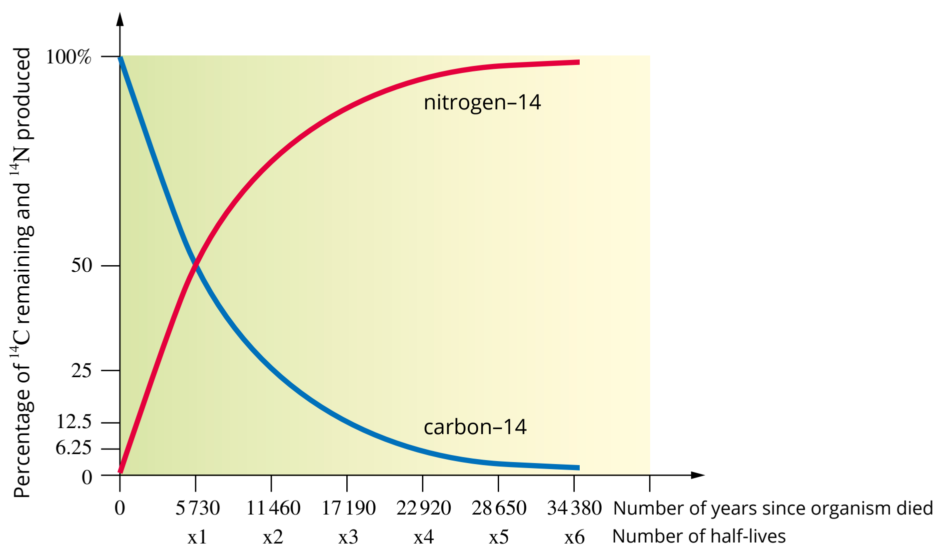

FIGURE 10.1.16 Carbon-14 (^{14}C) dating. From the time an organism dies, the amount of ^{14}C starts reducing at a known rate via decay to nitrogen-14 (^{14}N). The ^{14}C decays by half every 5730 years (its half-life), as shown in the graph. Carbon dating is only used for fossils younger than 50 000 years old.

- Thermoluminescence is a technique able to date objects such as pottery, cooking hearths and fire-treated tools up to 500 000 years old. Thermoluminescence is the emission of light from a mineral when it is heated. The amount of light emitted is proportional to the amount of radiation an object has absorbed: the older the object the more light it emits. The intensity of the light can be calibrated to reveal how much time has passed since the object was last heated or burnt in a fire. This technique is used to date artefacts related to human evolution.
- Electron spin resonance (ESR) is used to date calcium carbonate in limestone, coral, fossil teeth, molluscs and egg shells. Palaeoanthropologists have used ESR mostly to date samples from the last 300 000 years. Unlike thermoluminescence dating, the sample is not destroyed with ESR, allowing samples to be dated more than once.

Electron spin resonance (ESR) is a spectroscopic technique that detects atoms with orbitals containing unpaired electrons.

Information from fossils

Although fossils can indicate the appearance and structure of an organism, other information can be gained or inferred from examining fossils. For example, animal fossils have been found with young in the womb or inside eggs or guarding eggs (Figure 10.1.17). If young are fossilised next to adults, it is likely that the animal parented the young for a period (Figure 10.1.18). If large numbers of organisms are fossilised together, it could be assumed that they lived in herds. The contents of the animal's last meal may even be preserved in the fossil's stomach area.

FIGURE 10.1.17 A nest of fossilised dinosaur eggs with the remains of dinosaurs inside

FIGURE 10.1.18 This dinosaur nest with 15 one-year-old *Protoceratops andrewsi* discovered in the Djadokhta formation in the Gobi Desert, central Asia, suggests these animals were growing together with some sort of parental care.

BIOFILE CCT

Transitional fossils

There are notable examples of fossils that suggest significant stages in evolution, such as the transition from aquatic to land vertebrates. These fossils are interpreted as intermediate, or transitional.

Tiktaalik and *Acanthostega*

A 375-million-year-old fossil of the fish *Tiktaalik roseae* was discovered in Arctic Canada in 2004. It had gills and scales typical of a fish, but also limb-like fins, ribs, a flexible neck and a crocodile-shaped head like that of an early tetrapod (Figure 10.1.19a). *Tiktaalik* is seen as evidence of the period when aquatic vertebrates began moving ashore.

Acanthostega, of the late Devonian (Figure 10.1.19b), is one of the oldest known tetrapod fossils with recognisable limbs.

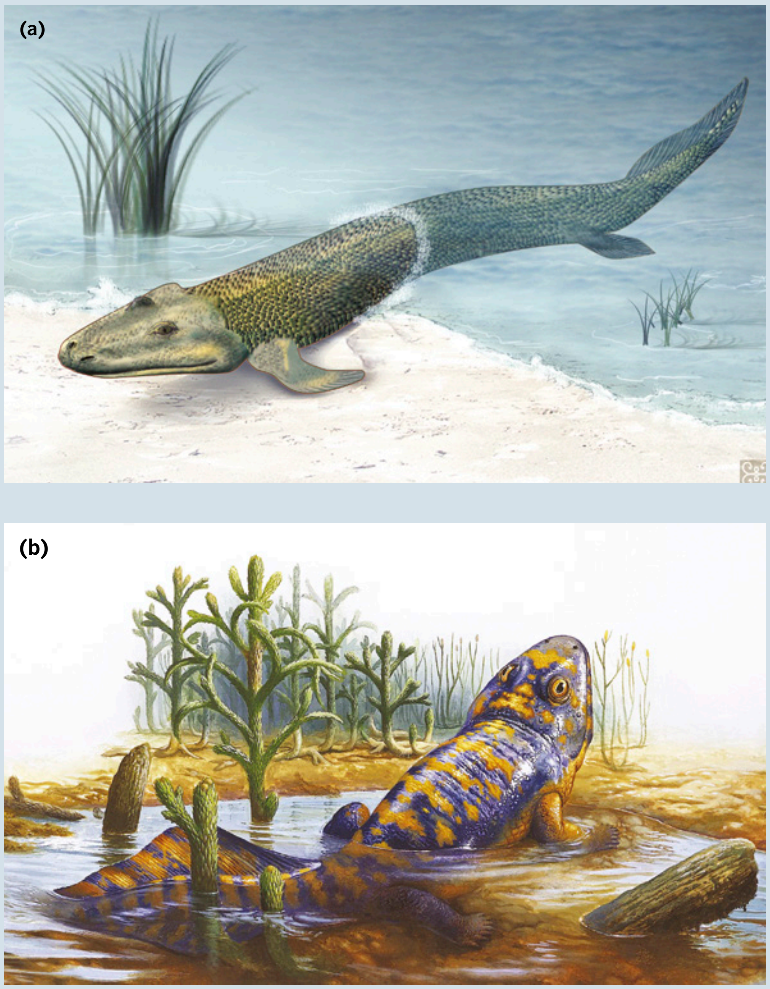

FIGURE 10.1.19 (a) *Tiktaalik* and (b) *Acanthostega. Acanthostega* was among the first vertebrates to evolve limbs and be able to move onto land.

The whale sequence

Fossil transitional series also show a return to the water, as in the case of whales (cetaceans) and their ancestors (Figure 10.1.20). This is also one of the best-documented of any fossil series.

Although the early cetaceans were not obviously whale-like, the relationship can be established via shared features that are unique to the group.

Roughly 50 million years ago, one family of even-toed ungulates (hoofed animals) split from the common ancestor with hippopotamuses. Most even-toed ungulates have since become herbivores, although the group was initially partly carnivorous. As largely terrestrial dog-sized whale ancestors became more and more committed to an aquatic lifestyle, they maintained their carnivorous diet. Meat was both readily available and provided the energy needed to live in water.

Adaptations to water at first included webbed feet, and denser bones that reduced buoyancy. Like their relatives the hippopotamuses, early whales lived in rivers.

Oxygen isotope data from *Ambulocetis* fossils indicates that the animals consumed both fresh and salt water, indicating a move towards the oceans. *Ambulocetis* also had a very limited ability to walk on land, and probably swam with a side-to-side motion like otters. From *Ambulocetis* onwards, cetaceans began to rely less on their legs, eventually losing them completely except for vestigial bones (Figure 10.1.20). Meanwhile, cetacean heads and sense-organs became increasingly specialised for a fully aquatic lifestyle.

The two most recent families shown in Figure 10.1.20 are the modern groups, baleen whales (Mysticeti) and toothed whales (Odontoceti), which diverged around 38.8 million years ago.

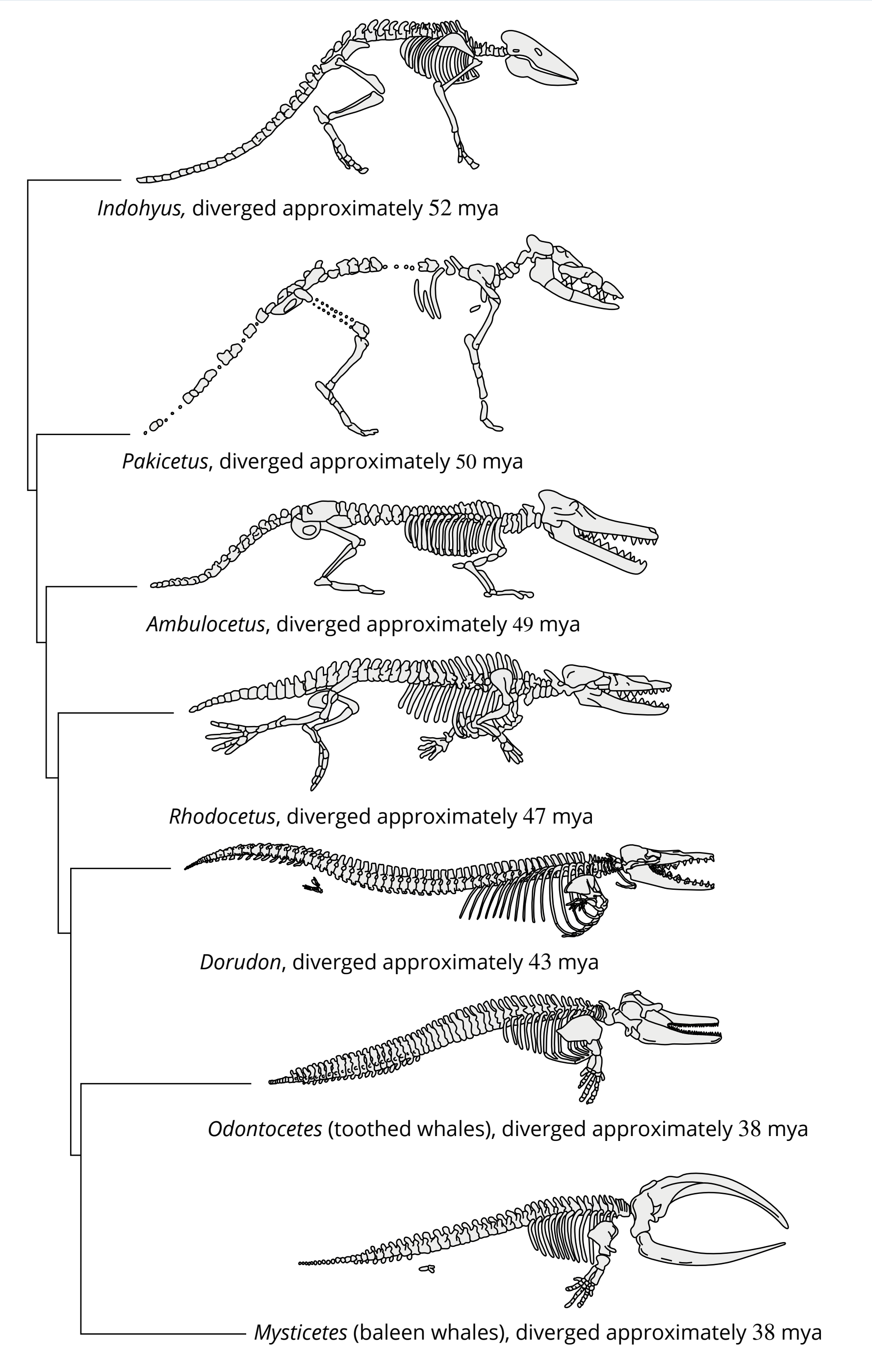

FIGURE 10.1.20 The evolutionary transition of land mammals to aquatic mammals (whales) (not to scale)

BIOGEOGRAPHY

Biogeography is the study of the geographic distribution of organisms and the factors that influence these distributions. Biogeography helps us to understand how the evolution and distribution of species has been shaped by geological processes, such as shifting continents, changing climates and fluctuating sea levels. This understanding can provide insight into the past as well as help us predict the distribution and success of species in the future.

Early biogeographers were interested in understanding how similar animals and plants in different parts of the world, separated by vast distances and huge oceans, came about. For example, they sought to understand why there are marsupial possums in Australia and South America, and whether or not the ostrich from Africa, the rhea from South America and the emu from Australia are related.

Patterns of evidence

When distributions of different groups of organisms in the world are mapped, patterns become evident that give clues to the evolutionary histories of the groups and of Earth itself. Observations by naturalists such as Alfred Russel Wallace led to the division of the world into six **biogeographic regions**: Palaearctic, Nearctic, Ethiopian, Indo-Malay, Neotropical and Australasian. There are now eight recognised biogeographic regions with the addition of the Oceanic region and the Antarctic region (Figure 10.1.21). Marine biogeographic regions include the tropical, temperate and Arctic zones, which differ in climate (Figure 10.1.21). Each region is recognised as having a unique set of related organisms, suggesting that the patterns are a result of evolution.

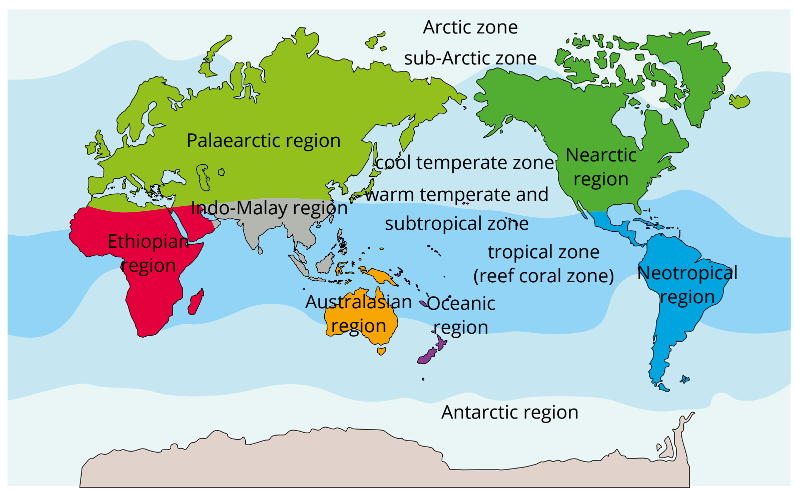

FIGURE 10.1.21 Biogeographic regions of the world's landmasses and oceans

Continental drift

Scientists noticed that the shape of continents appeared to fit together as if they had been cut from a single larger continent, known today as Pangaea (Figure 10.1.22). The west coast of Africa, for example, seemed to fit well against the east coast of South America. The implications of this were to become important evidence supporting the theory of evolution. If landmasses had at some point been joined, then it follows that organisms on continents separated today might share a common ancestry. Although the theory of **continental drift** had been proposed in the early 20th century, it was only confirmed much later by geological evidence and the study of plate tectonics. Australia, for example, once part of the southern supercontinent Gondwana, drifted from Antarctica and continues today to move northwards at a rate of approximately 3.7 cm/year for the western side and 5.6 cm/year for the eastern side. Geologists have been able to calculate the rate at which plates are moving and work backwards to determine the point at which the landmasses were joined. This information can help us understand how and when groups of organisms evolved in different parts of the world, and how they may be related to one another.

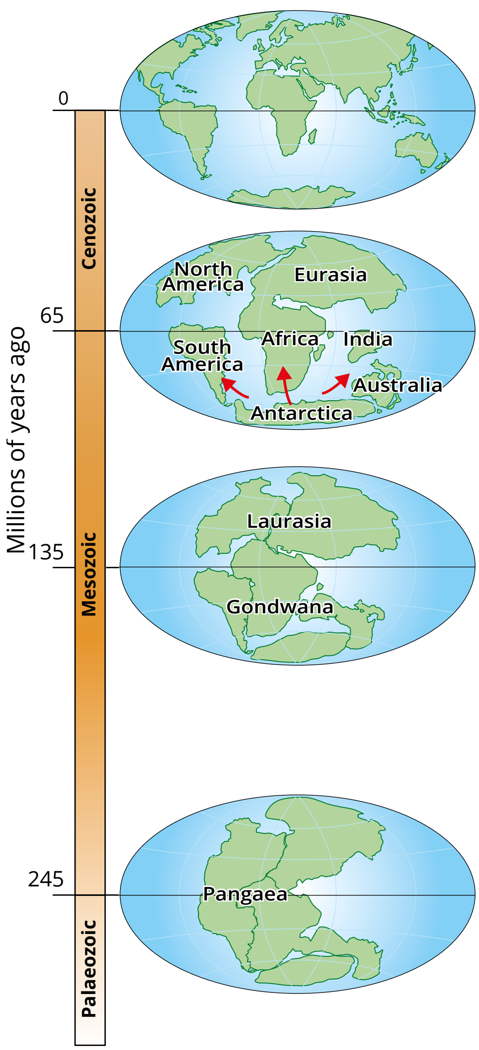

FIGURE 10.1.22 Pangaea and its break-up as crustal plates carrying continents and smaller pieces of land drifted apart

BIOFILE A CCT

Alfred Russel Wallace and Wallace's line

Alfred Russel Wallace independently proposed the theory of evolution by natural selection at about the same time as Charles Darwin. Wallace travelled through the Malay region collecting and studying the distributions of plants and animals. Based on his observations and those of other naturalists, he recognised that the world could be divided up into a number of biogeographic regions. Wallace mapped out a line, now known as Wallace's line, which is the boundary between the Australasian and Indo-Malay biogeographic regions (Figure 10.1.23a). This boundary marks the point where there is a difference in species on either side of the line (Figure 10.1.23b). To the west of the line, all of the species are similar or derived from species that are found on the Asian mainland, such as the streaked weaver bird. To the east of the line, there are many species that are of Australian descent, such as the Australian sulphur-crested cockatoo.

The Australasian and Indo-Malay biogeographic regions are on different tectonic plates (Figures 10.1.23a and 10.1.24) and have only recently come together. Although the two biogeographic regions are close today, they have previously been separated for millions of years. This separation explains the different fauna observed on either side of Wallace's line.

Although Wallace's line represents a significant contribution to our understanding of biogeography and evolution, the migration and distribution of species are not strictly limited by the line. Migratory species, such as birds and bats, are able to move between islands around Wallace's line, resulting in a zone where Indo-Malay and Australasian species come together. This group of islands sits between the tectonic plates of the Indo-Malay and Australasian regions and is known as Wallacea (Figure 10.1.23a).

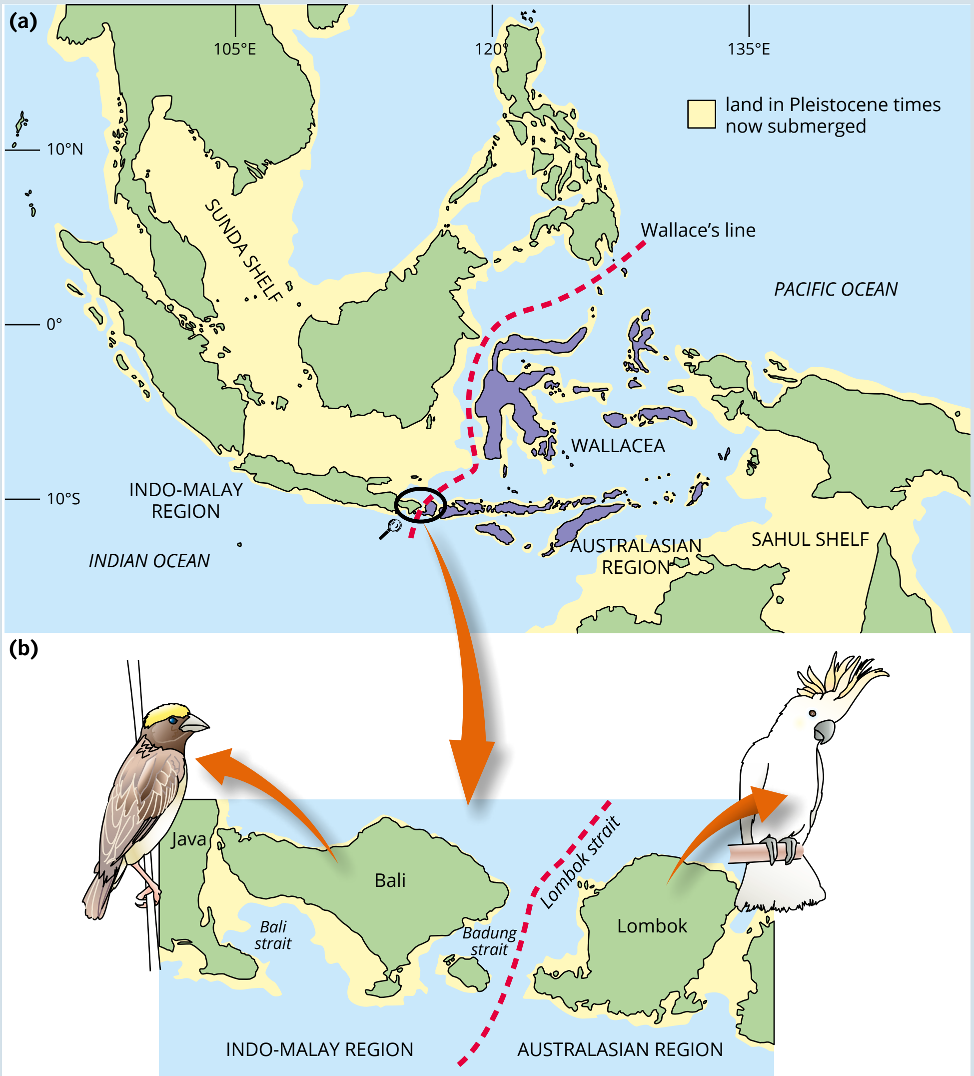

FIGURE 10.1.23 (a) Wallace's line (named after the biogeographer Alfred Russel Wallace) marks approximately the boundary between the Indo-Malay and Australasian biogeographic regions, where plates have collided. (b) The streaked weaver bird (*Ploceus manyar*) lives west of Wallace's line in south-east Asia while the Australian sulphur-crested cockatoo (*Cacatua galerita*) lives east of Wallace's line in Australia, Indonesia and Papua New Guinea. The islands Bali and Lombok are very close geographically but have different fauna and so are part of different biogeographic regions, separated by Wallace's line.

+ ADDITIONAL

Plate tectonics

Continental drift

The theory of continental drift was first developed by the geologist Alfred Wegner in 1912. However, his ideas were not accepted until the early 1960s when geological evidence of magnetic reversals and sea-floor spreading were documented.

It is now established that the crustal plates of Earth's surface move relative to one another, like ice floes (Figure 10.1.24). Australia, for example, rides on the top of the Indo-Australian plate, like a log embedded in an ice floe. The Indo-Australian plate also carries with it the southern part of New Guinea and surrounding parts of the Indian, Pacific and Southern oceans.

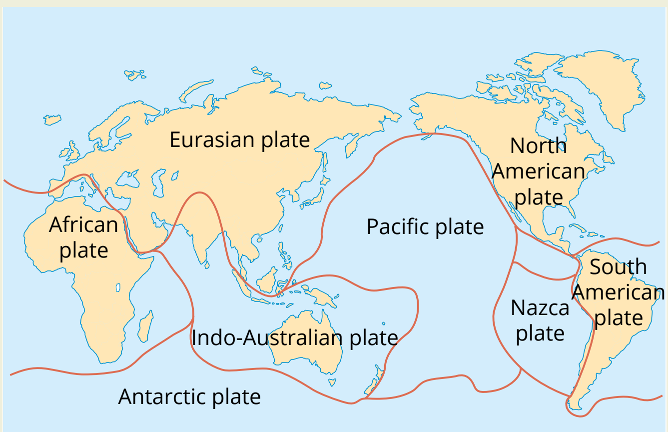

FIGURE 10.1.24 The major tectonic plates of Earth

Where two plates move apart (Figure 10.1.25a), material below Earth's crust upwells as a massive flow of lava. This new material forms a ridge marking the edge of two separating plates. Two plates may slide past one another or they may collide (Figure 10.1.25b). When they collide head-on, one plate may thrust under the other, forming a deep trench. Such trenches are the deepest parts of Earth's surface, the deepest plunging to more than 11 km below sea level in the western Pacific Ocean. Collisions may crumple the edge of the plate and create mountains. Earthquakes are also a result of plate movement. In 1906 an earthquake destroyed most of the city of San Francisco, which straddles a plate boundary.

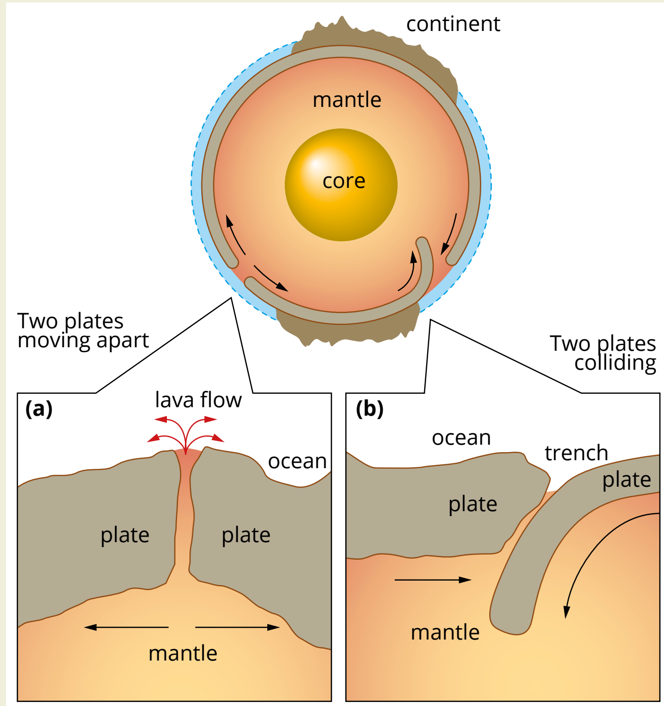

FIGURE 10.1.25 The plates of the Earth's crust float on the underlying mantle. Oceans and continents ride on top of these drifting plates. (a) Where two plates move apart, new material upwells as a lava flow. (b) Where two plates collide head-on, one slides under the other, returning material to the mantle.

Significance of plate movement

With our increasing understanding of Earth's crust and plate movement (plate tectonics), it is becoming possible to predict the occurrence and size of earthquakes. Knowledge like this may help to avert human tragedies. The most destructive earthquakes on record include the deaths of 830 000 people in China in 1556, 70 000 in Portugal in 1755 and 50 000 people in Iran in 1990. The disastrous earthquake near Sumatra in December 2004 tragically resulted in a tsunami that killed more than 200 000 people in Indonesia, Thailand, Sri Lanka and adjacent areas of the Indian Ocean. In March 2011, Japan suffered a severe earthquake due to the movement of the Pacific plate.

The theory of plate tectonics provides an explanation for the evolution of different groups of organisms. An important consequence of plate movement is that, throughout Earth's history, the positions of the continents have changed and oceans have been opened up or been lost. At least six times, the continents have come together to form supercontinents. They have then drifted apart, carrying plants and animals that had evolved by that time to new latitudes.

COMPARATIVE ANATOMY

If you compare the human body to that of a chimpanzee, you can see a striking resemblance in structure. The same applies to many other species, and this is more than a coincidence. Studying the **morphology** of species, or their body structures, gives an insight into the relationships between species. The field of comparing the structure of organisms is referred to as comparative morphology or **comparative anatomy**.

Homologous features

Features of organisms that have a fundamental similarity based on common ancestry are called **homologous features**. Often homologous features evolve different functions, but their similar structures provide evidence that the organisms shared a **common ancestor** from which they diverged over time. This is known as **divergent evolution** and is covered in Chapter 9.

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Mutations in the DNA sequences regulating the length of the bones in a limb can result in the limb being used in different ways. Close examination of tetrapod forelimbs, for example, shows that the same series of bones is present in each, but the genetic sequence has been modified, resulting in different structures with different functions.

For example, the forelimbs of all mammals, including humans, cats, whales and bats, show the same arrangement (with different lengths) of bones from the shoulder to the tips of the digits, even though these appendages have very different functions: lifting, walking, swimming and flying (Figure 10.1.27).

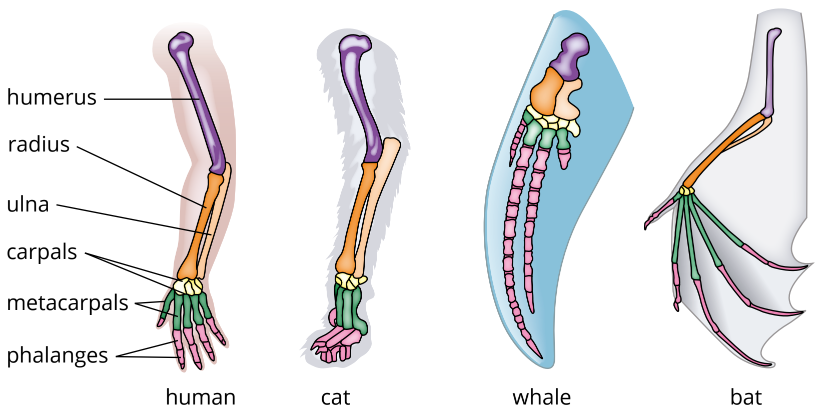

FIGURE 10.1.27 Even though they have become adapted for different functions, the forelimbs of all mammals are constructed from the same basic skeletal elements: one large bone (purple), attached to two smaller bones (orange and tan), attached to several small bones (yellow), attached to several metacarpals (green), attached to approximately five digits, each of which is composed of phalanges (pink).

Tetrapod refers to vertebrates with four limbs, including snakes and whales which evolved from four-limbed ancestors. The word 'tetrapod' is a combination of Greek and Latin words meaning 'four-footed'.

BIOFILE CCT S

The dugong

Based on comparisons of anatomy, the dugong (*Dugong dugong*) has the characteristics of a mammal (Figure 10.1.26). This is evidence of its evolutionary relationships. It is the only surviving species in its family (Dugongidae) and genus (*Dugong*), with its closest relatives being sea cows and manatees, which are classified in a separate family. The unique characteristics of these marine mammals evolved as they adapted to an aquatic life. The dugong lives in shallow seas in the Indo-Pacific region and is listed as an Endangered species.

FIGURE 10.1.26 The dugong (*Dugong dugong*) is a marine mammal.

Homologous features are evident in all groups of organisms. For example, the seeds of cycads, *Ginkgo*, conifer trees and flowering plants (angiosperms) show a variety of shapes and sizes but they have the same basic structure. The seeds of most conifers are winged and blown about by the wind, whereas the seeds of an *Acacia* lack a wing but have a tough outer coat and a coloured nutritious appendage to attract ants that disperse the seeds. Despite the variation, these plants all reproduce by seeds, and it can be argued that they have evolved from a common ancestral group (Figure 10.1.28).

FIGURE 10.1.28 Homologous structures in plants. (a) The seed of a fir tree has a large wing that allows it to be carried by the wind. (b) *Acacia* seeds are small and easily carried by ants. (c) Dandelion seeds have a light parachute attached that easily catches the wind.

Vestigial structures

Some organisms possess structures that seem to have little or no function. These structures are often remnants of organs that had a function in an ancestral species but have become reduced in size over time and have ceased to be used. Such structures are referred to as vestigial organs or **vestigial structures** and they provide further evidence of divergent evolution from a common ancestor.

Examples of vestigial structures include pelvic bones in whales and pythons (Figure 10.1.29); the coccyx, ear muscles, wisdom teeth and inner eyelid in humans; and the reduced eyes of certain blind cavefish and salamanders. Structures such as the wings of flightless birds can be considered vestigial for flight, but in many cases, such as that of the ostrich, the reduced wings provide a new function of temperature regulation.

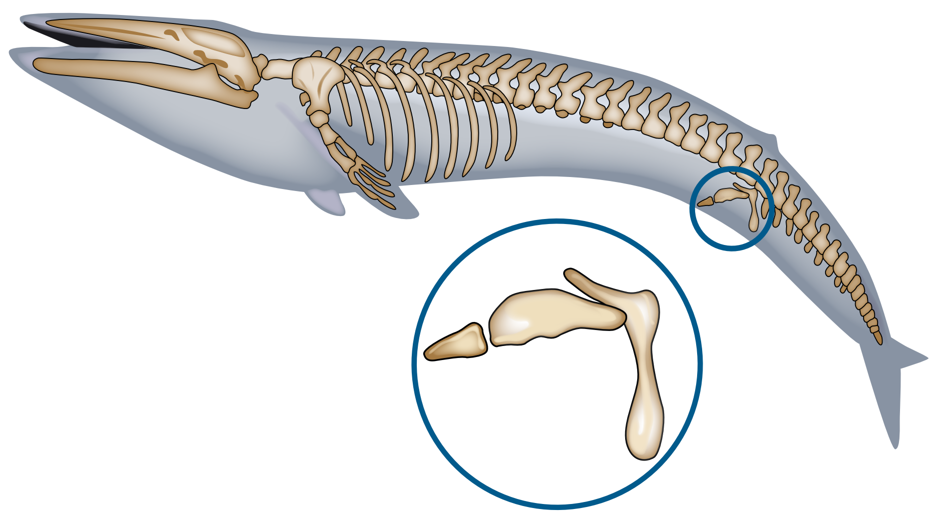

FIGURE 10.1.29 The skeleton of a baleen whale, a representative of the group of mammals that includes the largest living species, contains pelvic bones. These bones resemble those of other mammals, but are under-developed in the whale and have no apparent function.

BIOFILE CCT

Vestigial structures in humans

Charles Darwin listed a number of human vestigial features in his book *The Descent of Man* (1890). These included the appendix, wisdom teeth, tail bone, body hair, the fold in the corner of the eye and muscles of the ear (because humans can no longer rotate their ears like other vertebrates).

Some structures that have been identified as vestigial have since been found to have functions. For example, the human appendix is a remnant from our ancestor where it had a digestive function similar to the bacterial digestion of plant food in today's herbivores. Today surgeons only remove the appendix in extreme cases because it has been identified as having a role in immunity and the ability to store and protect beneficial bacteria in the gut.

BIOFILE CCT

Homologous features in birds and dinosaurs

By comparing skeletons, it was discovered that all dinosaurs and birds have a hole in their hip socket, known as an acetabulum, which allows the legs to descend straight down from the hips (Figure 10.1.30). No other four-legged vertebrate has this feature. The presence of an acetabulum is an example of a homologous feature in birds and dinosaurs: evidence that they shared a common ancestor.

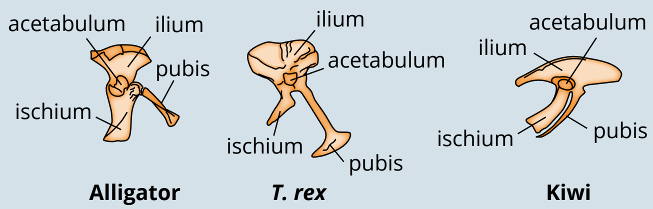

FIGURE 10.1.30 The acetabulum in the alligator, *Tyrannosaurus rex* and the kiwi, a bird

The common ancestry of birds and dinosaurs is even more obvious in *Archaeopteryx*, a fossil bird from the Jurassic, first found in Germany in 1860. *Archaeopteryx* possesses similarities to non-avian dinosaurs such as a long, feathered tail and small teeth. However, unlike non-avian dinosaurs, *Archaeopteryx* also has flight feathers and wings, just like a modern bird. The discovery of a fused clavicle bone in *Archaeopteryx* confirmed the relationship between birds and dinosaurs, as they are the only two groups to have this anatomical feature (Figure 10.1.31). In these groups, the clavicles are fused to form an elastic structure called the furcula, which stores elastic energy when the wing beats in flight. The furcula is the Y-shaped bone that we call the wishbone (Figure 10.1.31).

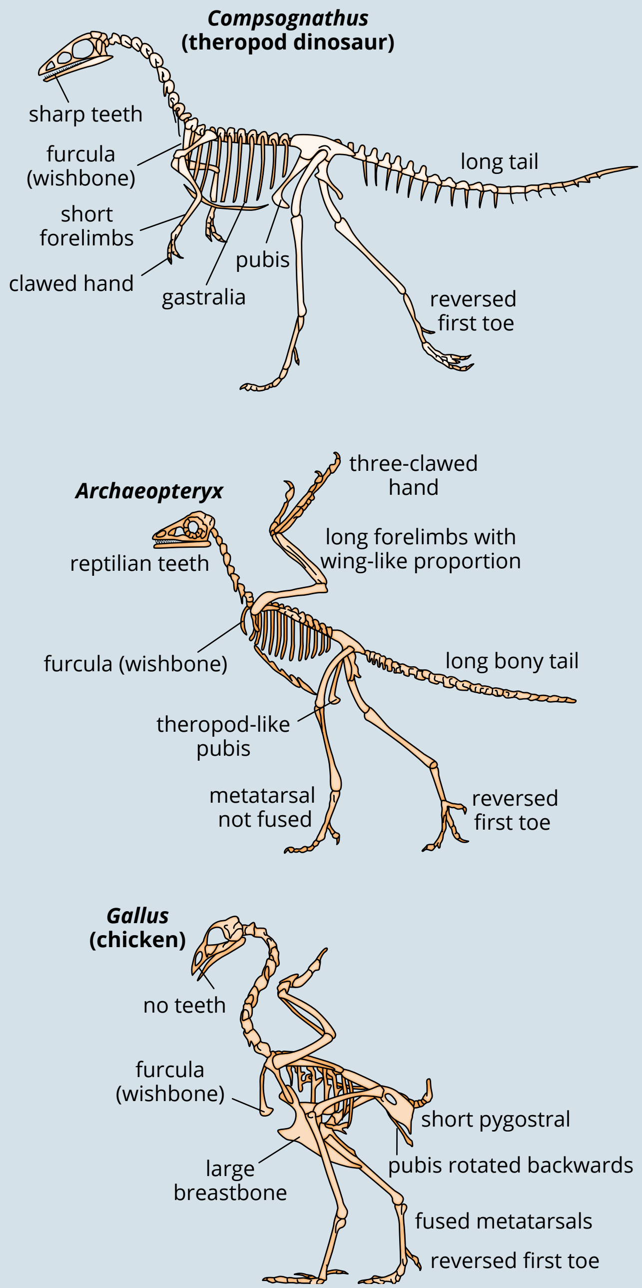

FIGURE 10.1.31 The skeletal structure of *Compsognathus* (therapod dinosaur), *Archaeopteryx* and *Gallus* (chicken) showing the structures that are similar between all three organisms

Homologous features are similar because the organisms share a common ancestor. Homologous features are retained through divergent evolution (divergence from a common ancestor).

Analogous features have a similar structure and function but evolved independently and do not share a recent common ancestor (e.g. bird and bat wings). This is a result of convergent evolution.

Analogous features

WS 3.7

Organisms can also show similarity that is not due to common ancestry. Flying animals such as butterflies and birds have wings (Figure 10.1.32). Fish and dolphins have swimming appendages and a streamlined body for moving through water. Many burrowing animals have powerful feet. Each of these features can be seen as an adaptation to a particular lifestyle.

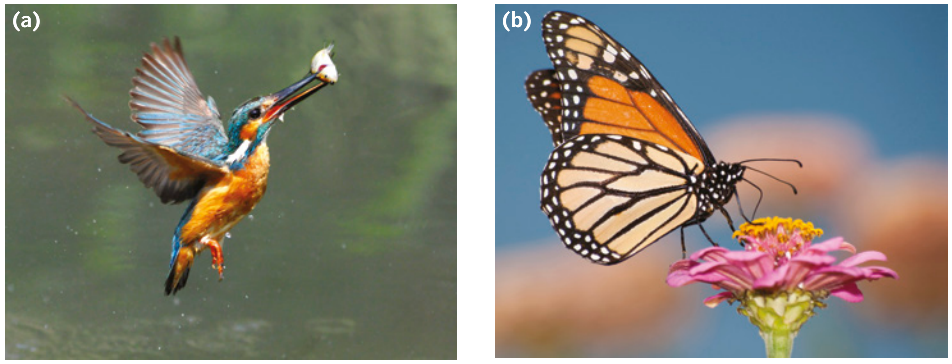

FIGURE 10.1.32 (a) The wings of a kingfisher allow the bird to fly and dive fast. This enables it to catch food, increasing its chances of survival. (b) A butterfly's wings allow the insect to travel between flowers in order to drink nectar.

FIGURE 10.1.33 Leopard lacewing (*Cethosia cyane euanthes*) life stage from caterpillar (top), to pupa (middle) and adult butterfly (bottom)

Anatomical structures that are found in different groups of organisms, such as wings in birds and butterflies, are described as **analogous features**; that is, they serve the same function but have evolved independently. Analogous features may evolve because unrelated organisms have experienced similar selection pressures. Thus, when biologists attempt to work out evolutionary relationships, they must distinguish between homologous and analogous features. Identifying features as analogous provides evidence of a convergent pattern of evolution but not evidence of descent from a common ancestor. **Convergent evolution** occurs when similar features evolve independently in unrelated groups of organisms. Convergent evolution is examined in Chapter 9.

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COMPARATIVE EMBRYOLOGY

The comparison of organisms is complicated by the way organisms change substantially between life stages. The metamorphosis of a tadpole to a frog or a caterpillar to a butterfly are examples of this (Figure 10.1.33). The field of biology that studies the development of a **zygote** to the form of an adult is called **developmental biology**. To study evolutionary relationships the **embryo** development of different species is compared. This field of study is known as **comparative embryology**.

Homologous structures can sometimes be seen in the embryo of species but not in the adult form. When two gametes (egg and sperm) fuse, a zygote and eventually an embryo forms. The development of an embryo is controlled by a series of master genes that organise the position and rate of growth of cells. Organisms that shared a common ancestor often have similar master genes. This means that the embryos will pass through similar stages of development. A human embryo, for example, passes through a stage in which it has gill slits like those of a fish (Figure 10.1.34). Comparative embryology is therefore an important source of evidence of evolutionary relationships.

FIGURE 10.1.34 The embryos of four vertebrates in three stages of development are remarkably similar and are used as evidence of common ancestry: (a) pig, (b) cow, (c) rabbit and (d) human. These drawings by the zoologist Ernst Haeckel were published in the 19th century. Modern studies confirm his observation that embryonic structures in early stages of vertebrate development are very similar; for example, all vertebrates at some stage develop pharyngeal slits, which later take on different functions in the different organisms.

BIOCHEMICAL EVIDENCE

Before **biochemical** or **molecular** techniques were available, structural (morphological) and functional similarities were the main evidence used to determine relatedness. Humans, chimpanzees, gorillas and orangutans each have forelimbs with hands and five digits (fingers). These morphological similarities can be used as evidence to support the theory that humans are related to the great apes and are descended from a common ancestor. Biochemical evidence, such as **DNA sequences**, reflects the similarity in the morphology of humans and great apes, indicating that these groups have indeed diverged from a common ancestor.

However, anatomical similarities can also be due to convergent evolution of organisms that did not share a recent common ancestor. A shark and a dolphin, for example, have a similar shape suited to living and swimming in water (Figure 10.1.35). Despite an overall similarity of appearance due to living in similar environments and experiencing similar selection pressures, sharks and dolphins have very different DNA sequences, indicating that they are not closely related. Similar morphological features can result from shared ancestry (homologous features) or from independent evolutionary paths (analogous features) so biochemical evidence plays an important role in clarifying uncertain evolutionary relationships.

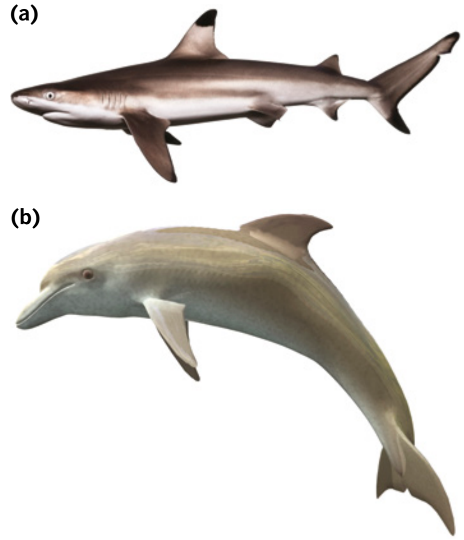


FIGURE 10.1.35 Although the shark (a) and the dolphin (b) appear to have similar features, they have very different DNA sequences. This indicates that they are not closely related and the anatomical similarities between these species are due to convergent evolution rather than shared ancestry (divergent evolution).

Determining relatedness between species using molecules

If species have a very similar set of proteins, **chromosomes** or DNA sequences, it is evidence that they shared a recent common ancestor. Recent, in evolutionary terms, may be hundreds of thousands, even millions, of years.

All living organisms on Earth once shared a common ancestor. If two populations become isolated from each other, they will accumulate different mutations in their DNA. As time passes, the sequence of **nucleotides** in their DNA becomes more different and what was once similar DNA gradually diverges (Figure 10.1.36). The more mutations that accumulate in the DNA sequences between two species, the more time will have passed since the two species diverged from their common ancestor. For example, there are more differences between the DNA sequence of a frog and a dog, than between a frog and a toad. This is because a dog and a frog have a more distant common ancestor than a frog and a toad and have therefore had more time to accumulate genetic changes.

Changes in nucleotide sequences are caused by mutations. When a cell copies its DNA, it may make errors. Usually these errors are repaired before **mitosis** (cell division) occurs. Occasionally these errors are not repaired and become a permanent part of the **genome**. This is a mutation. If these mutations occur within the germ line cells (cells involved in the production of eggs and sperm), then they can be passed on to the next generation.

> Nucleotides are the building blocks of DNA and RNA. Each nucleotide consists of a sugar (deoxyribose in DNA and ribose in RNA), a phosphate group and a nitrogenous base. The nitrogenous bases are adenine (A), cytosine (C), guanine (G) and thymine (T). In RNA, thymine (T) is replaced with uracil (U).

> Mutations occur regularly as a species evolves: like 'molecular clockwork'. As time passes, mutations accumulate in DNA, resulting in genetic differentiation and divergence of species.

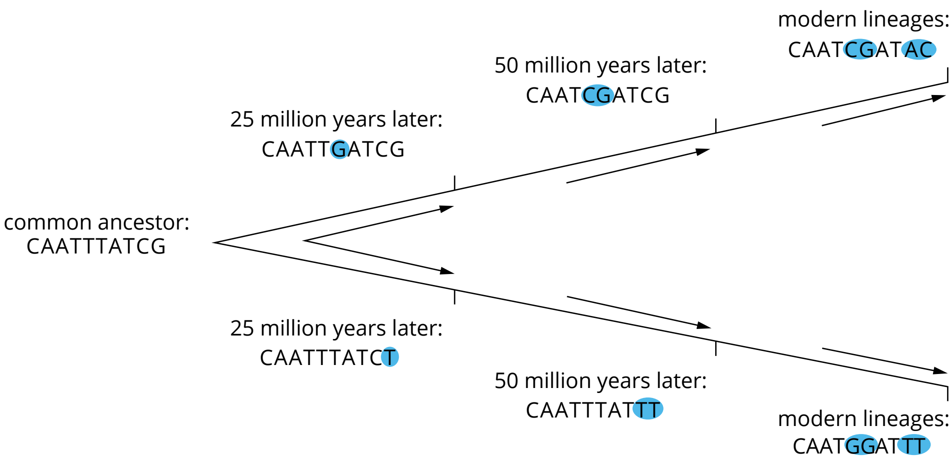


FIGURE 10.1.36 When species diverge, they start accumulating different mutations in their nucleotide sequences. The more time that passes, the more mutations they accumulate.

BIOLOGY IN ACTION CC S

Ancient DNA from Extinct giant kangaroo and wallaby

Ancient DNA has been extracted from the bones of a giant short-faced kangaroo (*Simosthenurus occidentalis*) and a giant wallaby (*Protemnodon anak*) that inhabited Australia about 40 000–50 000 years ago (Figure 10.1.37). This research was conducted by scientists from the University of Adelaide's Australian Centre for Ancient DNA (ACAD) and provides us with new insight into the evolutionary past of Australia's megafauna (Figure 10.1.38).

Remains of the giant short-faced kangaroo and giant wallaby were discovered inside a cave in Mount Cripps, Tasmania. The cool, dry conditions of the cave preserved the remains, allowing the researchers to extract the DNA from the ancient bones and reconstruct part of the mitochondrial genomes of both species. This is the first glimpse into the DNA of the Australian megafauna; previous attempts to sequence genetic material were unsuccessful due to the poor preservation of the specimens. Well-preserved megafauna specimens are rarely found in Australia due to the harsh climate and age of the remains (39 000–52 000 years). The specimens in this study are the oldest Australian remains from which DNA has been sequenced.

Information from the mitochondrial genome of the giant wallaby revealed that it is a close relative of the living genus *Macropus*, which includes grey and red kangaroos and the tammar wallaby. DNA evidence confirmed that the short-faced kangaroo belongs to the extinct subfamily Sthenurinae. Although the short-faced kangaroo has no living descendants, its closest living relative is the Endangered banded hare-wallaby, the only surviving member of the ancient subfamily, Lagostrophinae. The banded hare-wallaby is now restricted to islands off the coast of Western Australia and is the last representative of a once-diverse lineage of ancient kangaroos.

Ancient DNA gives us insight into the past, but it also strengthens our understanding of the evolutionary history and biology of living species. This knowledge has applications in conservation and environmental management, as we learn from the past to predict the future.

FIGURE 10.1.37 The short-faced kangaroo (*Simosthenurus occidentalis*). Fossil remains of this species were discovered in a cave in Tasmania.

FIGURE 10.1.38 Researcher Dr Bastien Llamas with a skull of the Extinct giant short-faced kangaroo (*Simosthenurus occidentalis*). Scientists extracted and sequenced ancient DNA from this species to understand its evolutionary relationship with living and extinct fauna.

DNA and amino acid sequences

As two species diverge from a common ancestor, they accumulate different mutations in their DNA and **amino acids**. DNA carries the code for amino acids and amino acids are the building blocks of proteins. Changes in the DNA sequence may lead to changes in amino acids and the proteins synthesised. In this way, DNA mutations can lead to changes in an organism's **phenotype** (features). Sometimes **point mutations** in the DNA sequence, such as **nucleotide** substitutions, insertions or deletions, may not cause a difference in the amino acid sequence. This is because the genetic code is degenerate, which means more than one **codon** (triplet DNA sequence) codes for the same amino acid; for example, GUU, GUC, GUA and GUG all code for the amino acid valine. Consequently, differences in amino acids accumulate more slowly than differences in DNA.

Amino acid changes that do not cause a change in the protein are called **conservative substitutions**. **Semi-conservative substitutions** result in an amino acid being replaced by one that is similar in structure but has different biochemical properties. This may lead to a change in the protein. **Non-conservative substitutions** result in an amino acid being replaced by one that is very different and this usually leads to major changes in the protein and its function.

Even when a point mutation leads to a change in an amino acid, the mutation may not lead to a change in phenotype. All mammals, for example, produce milk containing the protein casein, suggesting that all mammal species have the same gene for this protein. However, if the DNA sequence that makes up this gene is compared, slight differences might be observed. For this reason, and because it is now technically easier and cheaper to analyse nucleic acids than proteins, DNA comparisons are the preferred type of data.

Modern sequencing techniques provide an accurate measure of genetic differentiation between organisms. The exact number of nucleotide differences between organisms can be determined by comparing their nucleotide or amino acid sequences. Figure 10.1.39 shows an alignment of five organisms' amino acid sequences. The amino acid sequence shown is from the mammalian histone protein family, H1. Histones play important roles in DNA packaging and gene regulation. The evolutionary relationships between the organisms can be estimated by comparing the number of differences in their amino acid sequences.

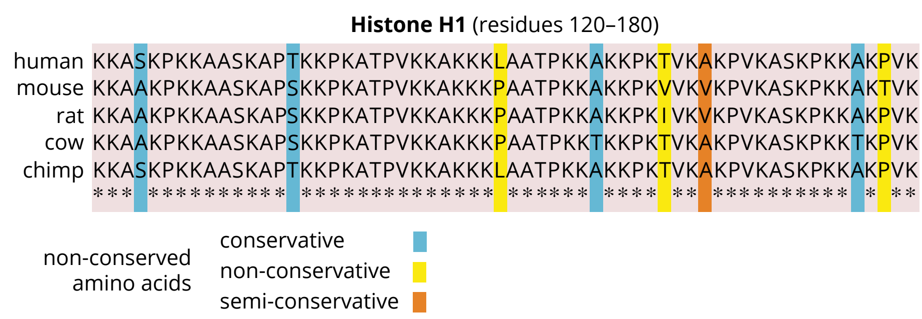


FIGURE 10.1.39 Amino acid alignment of part of the mammalian histone protein family, H1. Amino acids for which there has been no change are indicated by an asterisk. Conservative amino acid substitutions are indicated in blue, non-conservative substitutions are indicated in yellow and semi-conservative substitutions are indicated in orange. The organisms that share a more recent common ancestor have fewer differences in their amino acid sequences (e.g. mouse and rat compared to rat and cow).

Table 10.1.1 shows the number of amino acid differences in the mammalian histone protein family, H1, between humans, mice, rats, cows and chimpanzees. From this data, the evolutionary relationships of these organisms can be inferred. For example, there are six amino acid differences between humans and mice in H1 but zero between humans and chimpanzees. This indicates that humans have a closer evolutionary relationship with chimpanzees than with mice. The amino acid sequence data from H1 reflects what is understood about the evolutionary relationships of these organisms from comparative anatomy, comparative embryology and other biochemical evidence.

TABLE 10.1.1 The number of amino acid differences in the mammalian histone protein family, H1, of different organisms

	Human	Mouse	Rat	Cow	Chimpanzee
Human	0				
Mouse	6	0			
Rat	5	2	0		
Cow	5	5	4	0	
Chimpanzee	0	6	5	5	0

Not all DNA mutations lead to changes in amino acids and proteins. This is because each amino acid has multiple DNA codes; a change in one nucleotide in the code may not change the amino acid.

+ ADDITIONAL

Chromosomes in common

Homologies between chromosomes of different species can also be used as evidence of relatedness between species. To analyse condensed chromosomes, they are first stained with a dye called Giemsa stain. Some regions of the DNA take up more stain than other regions and appear as dark horizontal bands (Figure 10.1.40). The pattern of bands reflects the structure of the chromosome.

Chromosomes can be identified by three features:

- their length
- the location of the centromere (middle section of a chromosome, where the two **chromatids** join)
- the dark sections of the chromosome (banding).

Organisms that shared a recent common ancestor will have many chromosomes in common. A common ancestor is evident when comparing length and banding of human and chimpanzee chromosomes. Although humans have 46 chromosomes and chimpanzees 48, there are many similarities in the banding of the chromosomes of the two species (Figure 10.1.41). The difference in the number of chromosomes can be accounted for by comparing human chromosome 2 with two smaller chimpanzee chromosomes, which have the same banding pattern.

Other apes that diverged from a common ancestor to the chimpanzees also have these two chromosomes (Figure 10.1.41). This indicates that in a common ancestor the two smaller chromosomes may have joined together, giving rise to one of the early human ancestors, and leading to the divergence of the two lineages.

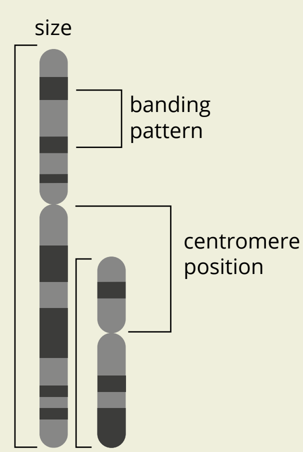


FIGURE 10.1.40 When preparing a karyotype, scientists compare the number and size of the chromosome, the banding pattern and the position of the centromere.

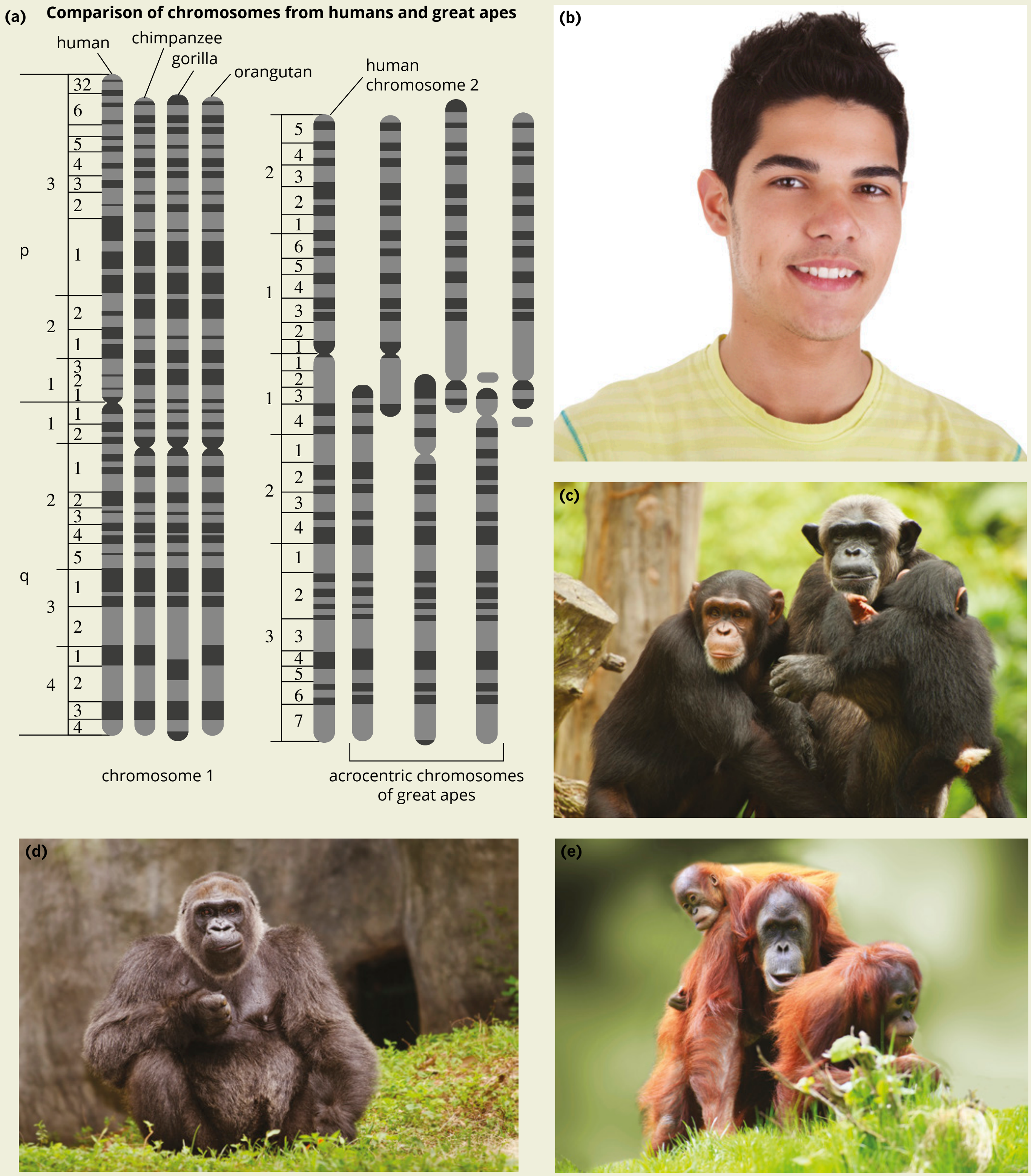


FIGURE 10.1.41 (a) A comparison between the karyotypes of (b) humans, (c) chimpanzees, (d) gorillas and (e) orangutans reveals many similarities between these species. Human chromosome 2 has similar banding patterns to two chromosomes of the chimpanzee, gorilla and orangutan. (Acrocentric chromosomes are chromosomes with centromeres near the end, rather than the middle.)

Molecular clocks

A **molecular clock** is a technique that uses the rate of accumulation of mutations in DNA to calculate how long ago organisms diverged from one another. The molecular clock hypothesis is the basis of this technique and was first proposed in the 1960s by Emile Zuckerkandl and Linus Pauling. This hypothesis states that changes in DNA and proteins are constant over evolutionary time and across different lineages.

The change in DNA over time is also known as the **mutation rate** and can be expressed as the number of nucleotide changes that occur every million years. The molecular clock hypothesis can be applied by calculating the rate of mutation of a region of DNA, along with the number of differences between the DNA of two organisms, and using this information to estimate how long ago they diverged (Figure 10.1.42). The more unique mutations each species accumulates, the more time has passed since they shared a common ancestor.

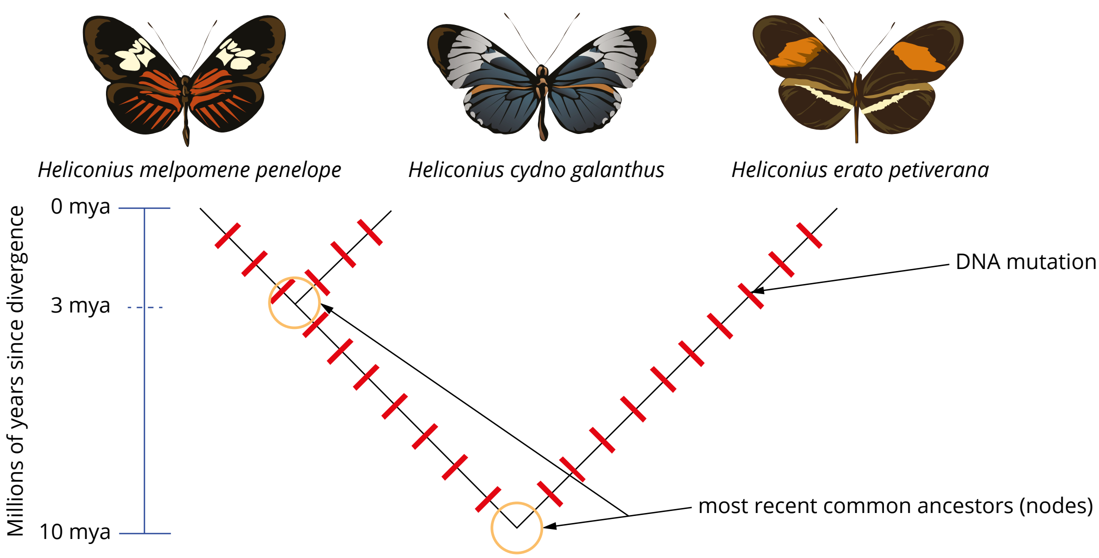


FIGURE 10.1.42 This diagram illustrates the evolutionary relationships between three butterfly species. Each mutation in the DNA sequences used to construct this evolutionary tree is represented by a red line. The time scale (millions of years) over which the divergence occurred is to the left of the tree. The mutation rate can be calculated from the number of mutations that have accumulated over the evolutionary time period. The most recent common ancestors are represented by the nodes (branching points).

In order to estimate how long ago two lineages diverged, the molecular clock is calibrated using evidence from the fossil record. Techniques such as radiometric dating and stratigraphy (the study of rock layers) are used to date fossils. The molecular clock for a particular gene can then be calibrated by comparing the number of differences in DNA sequences with the dates of evolutionary branch points known from the fossil record of similar organisms.

Limitations of molecular clocks

The molecular clock is a useful **phylogenetic** tool but it does have some limitations. One of its major limitations is the assumption that the rate of genetic change is constant and therefore accurately represents evolutionary time (Figure 10.1.43). Although we know that genetic difference represents evolutionary distance and that both these factors are positively correlated with time (i.e. the greater the difference between organisms, the more time has passed since they last shared an ancestor), the rate of genetic change over time is not always constant. This means that genetic change is not an accurate measure of time from which we can determine exact dates of lineage divergence.

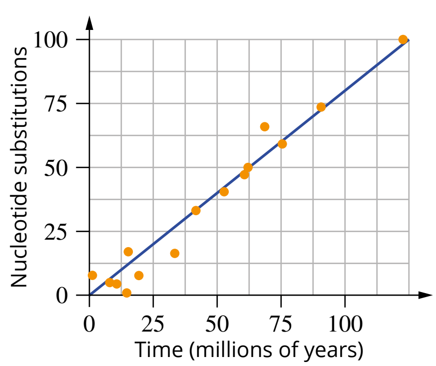


FIGURE 10.1.43 The constant rate of genetic change (nucleotide substitution) over time (millions of years) assumed under the molecular clock hypothesis. Regions of neutral genetic variation undergo relatively constant rates of genetic change; however, this does not apply to many coding regions of DNA.

In order for genetic changes to occur at a constant rate, those changes (mutations) need to be neutral or not affected by natural selection. This needs to be considered when applying a molecular clock to genetic data. Any DNA regions that code for the phenotype of the organism (i.e. its structure or function) are under natural selection and will change according to outside selection pressures. Therefore, the mutation rate of proteins and protein-coding DNA (genes) will not be constant.

Some sections of DNA mutate more frequently than others: that is, at a faster rate. This means there are different molecular clocks within an organism, ticking at different speeds in different regions of DNA. Genes that are essential to an organism's survival, such as those that code for cytochrome *c*, very rarely accumulate mutations and the gene sequence is therefore highly conserved (mostly unchanged) throughout evolution (Figure 10.1.44). Any variations to the sequence of these essential genes may result in these proteins losing function and the organism dying. For example, changes in cytochrome *c* may cause the electron transport chain to fail, preventing the formation of ATP. As a result, the organism will die. Sections of DNA that are not essential to the survival of an organism accumulate mutations at a faster rate. As a consequence, there are many molecular clocks within each organism that run at different rates.

The molecular clock is also limited when looking at very recent or ancient timescales. When looking at recent timescales, it is less likely that enough time has passed to generate evolutionarily meaningful fixed differences in the sequences of different populations. Instead, alternative **alleles** that may be present in both populations will lead to an overestimation of evolutionary distance. Over ancient timescales, single sites in the sequence will have changed multiple times and this is known as saturation. Because we can only know of those changes that can be observed today, a molecular clock will underestimate the divergence that has occurred.

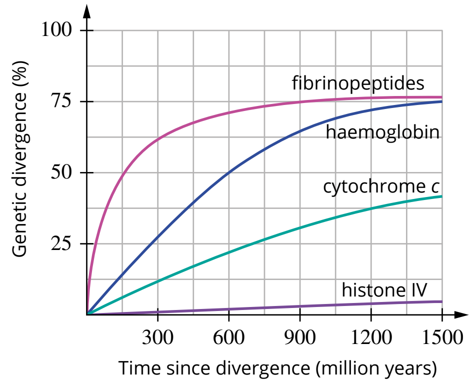


FIGURE 10.1.44 Different proteins mutate at different rates. This graph shows the rate of genetic divergence (%) of different proteins over evolutionary time (millions of years since divergence). The graph shows the rapid mutation rate (% genetic divergence) of fibrinopeptides compared to the slower rates of mutation of haemoglobin, cytochrome c and histone IV. The proteins with the slower rates of mutation accumulation are highly conserved, indicating that they are involved in functions that are essential to the survival of the organism.

Mitochondrial DNA as a molecular clock

Genetic material is not just found in the nucleus of a cell. Mitochondria found in eukaryotic cells have their own genome (**mitochondrial DNA** or mtDNA). In humans, mtDNA contains 37 genes that code for 2 ribosomal RNAs, 22 transfer RNAs and 13 proteins.

MtDNA is unique in that it is passed through the maternal line of sexually reproducing organisms; that is, from mothers to their offspring (Figure 10.1.45). A father's mtDNA is not passed on to his offspring.

Mutations in mtDNA accumulate over time just as they do in nuclear DNA. However, because mtDNA does not have the same repair mechanisms as nuclear DNA, the rate of mutation in mtDNA is usually higher than in nuclear DNA (there are also some highly conserved regions). For this reason, mtDNA can be used as a molecular clock in relatively closely related species, while nuclear DNA is used to compare older lineages. An added advantage of using mtDNA is that it is easier to obtain high yields of DNA because most cells contain many mitochondria.

Mitochondrial DNA is inherited via the maternal line, while nuclear DNA is passed on from both parents (biparentally inherited).

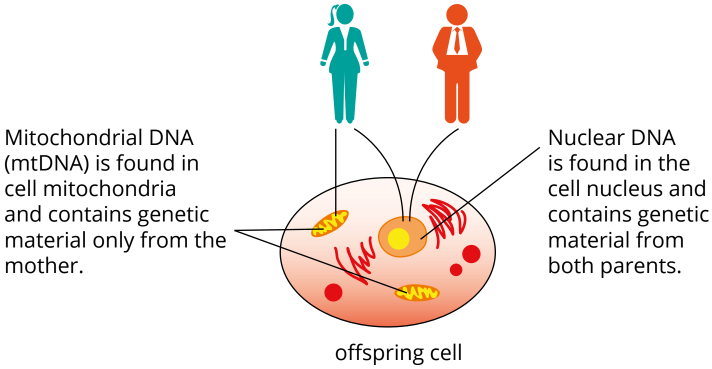


FIGURE 10.1.45 When a sperm and egg fuse, the sperm contributes nuclear DNA only. The egg contributes nuclear DNA as well as the mtDNA of the mitochondria in its cytoplasm. Therefore, mtDNA is only inherited through the maternal line; nuclear DNA is inherited from both parents.

BIOFILE CCT

Mitochondrial Eve

Mitochondrial Eve is the most recent common female ancestor of all present-day humans. As mitochondrial DNA (mtDNA) is inherited from the mother (maternally inherited), there is no recombination, making it possible to trace unbroken maternal lines. In 1987, researchers from the University of California, Berkeley, discovered that the mtDNA of all living humans originated from one woman who lived in Africa approximately 140 000 to 200 000 years ago (Figure 10.1.46).

Although Mitochondrial Eve represents an unbroken female lineage from one woman until the present day, she was not the only female alive at the time nor the earliest female. Other women who came before her or were alive at the same time have not had a continuous female lineage that persisted to the present day. This is because if a woman does not have daughters who also have daughters to pass on her mtDNA, her mitochondrial lineage will die out. It is for this reason that the most recent common ancestor (matrilineal or otherwise) will continually shift over time as lineages end and others carry on.

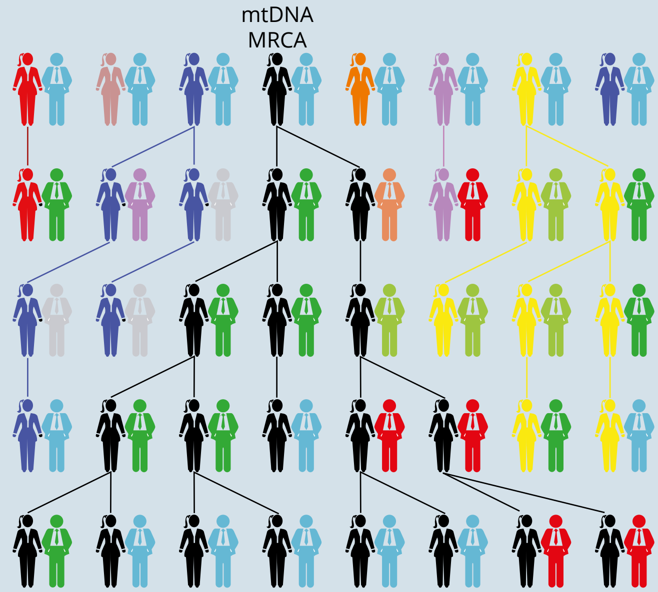


FIGURE 10.1.46 Tracing mitochondrial lineages over five generations. The coloured figures represent extinct mitochondrial lineages, while the black figures represent the female line that is directly descended from the most recent common mitochondrial ancestor (MRCA).

Phylogenetic trees

Phylogenetic trees (or phylogenies, also known as evolutionary trees) are branching diagrams that depict the evolutionary relationships between different groups of organisms. They are constructed using homologous features, both morphological and molecular, to reveal the branching history of common ancestry between groups of organisms. As information regarding the true evolutionary history of an organism is mostly unknown, scientists use evidence from the morphology and DNA or RNA sequences of living species to reconstruct their evolutionary past. A phylogenetic tree represents an evolutionary hypothesis.

Today, most phylogenetic trees are built using DNA or RNA sequence data, and organisms are grouped on the basis of the similarity of their nucleotide sequences. Using this technology, we have gained remarkable insight into the evolutionary history of life on Earth.

Building phylogenetic trees

A phylogenetic tree is built by placing organisms in a branching sequence, according to their shared biological characteristics (morphological or molecular). A simple example using morphological characters is seen in Figure 10.1.47. By assessing the characters that different organisms share, the evolutionary relationships between organisms can be hypothesised. Starting with the most shared character, which is assumed to be the most ancestral, organisms are added to the tree sequentially, ending with the least shared character at the top of the tree (Figure 10.1.47). In Figure 10.1.47, the most-shared (ancestral) character is the vertebral column and the least-shared character is hair. Each branch in the tree represents a change in character state from the last common ancestor.

(a) Character table

Characters \ Organism	seastar (outgroup)	lamprey	shark	frog	chicken	dog
hair	0	0	0	0	0	1
amniotic (shelled) egg	0	0	0	0	1	1
four walking legs	0	0	0	1	1	1
jaws	0	0	1	1	1	1
vertebral column (backbone)	0	1	1	1	1	1

(b) Phylogenetic tree

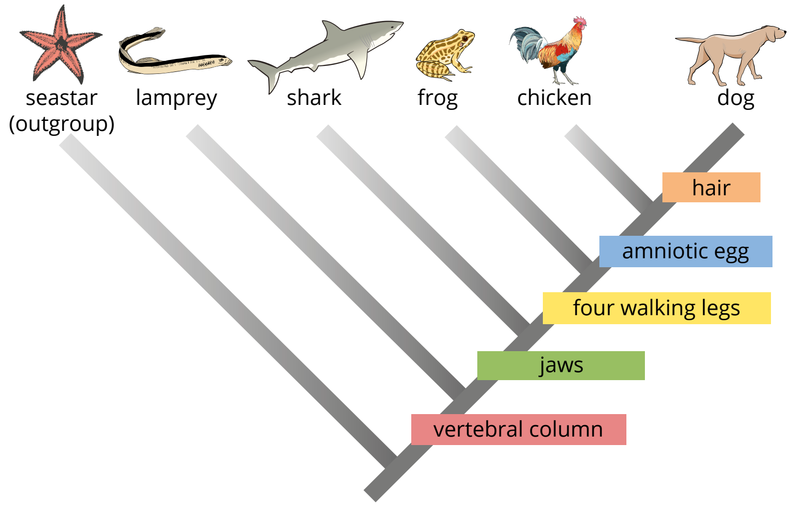


FIGURE 10.1.47 Building a simple phylogenetic tree using morphological characters. (a) A character table lists different morphological characters and their presence (1) or absence (0) in each taxon is indicated. (b) Each taxon is sequentially added to the tree according to the presence of shared characters, which are assumed to reflect when they appeared in evolutionary history. The more ancestral the character, the more likely it is to be present in a greater number and variety of organisms (e.g. all organisms except the most ancestral group—seastar—have a vertebral column, so this character is assumed to be the most ancestral and placed at the base of the tree).

Phylogenetic trees based on molecular characters (DNA or RNA nucleotides) can be used to compare any organism, even if they seem to have very few characteristics in common. The greater the number of nucleotide differences between DNA or RNA sequences, the greater the distance between them in the tree, reflecting their evolutionary relationships (Figures 10.1.48 and 10.1.49). Most phylogenetic trees are now built using computational methods to generate complex trees from large datasets of thousands of nucleotides.

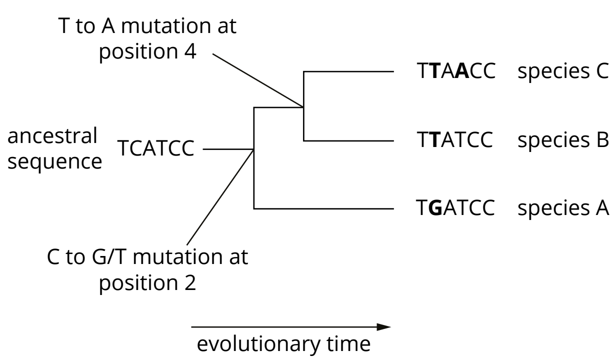


FIGURE 10.1.48 Phylogenetic trees can be built using DNA or RNA sequence data to estimate the evolutionary distance between organisms. In this phylogenetic tree the ancestral nucleotide C (position 2) has been substituted for G in species A and a T in species B and C, indicated by the first branch point. Another mutation, T to A, is represented by the second branch point and the divergence of species B and C. The greater the number of nucleotide differences between organisms, the greater the distance between them in the phylogenetic tree. DNA sequences used to construct phylogenetic trees are much longer than represented here.

Figure 10.1.49 shows the evolutionary relationships between four groups of plants: three flowering plants and a pine tree. The pine tree (*Pinus* sp.) has the longest branch in the phylogenetic tree, indicating it is the most ancient lineage and the most closely related to the common ancestor. This evidence supports what is understood about the evolution of flowering plants from non-flowering plants. The eucalypt (*Corymbia* sp.) is the most ancient flowering plant represented in the phylogenetic tree (Figure 10.1.49b) and the bean plants (*Vigna* sp. and *Glycine* sp.) are the most recently diverged group with the most similar DNA sequences (Figure 10.1.49a).

(a)

	1	2	3	4	5	6	7	8	9	10	11
(eucalypt) *Corymbia*	C	C	C	–	T	C	T	T	T	T	T
(mung bean) *Vigna*	C	T	C	T	T	T	T	T	T	C	A
(soya bean) *Glycine*	C	T	C	T	T	T	T	T	A	C	G
(pine tree) *Pinus*	C	C	T	–	C	C	C	C	C	C	C

(b)

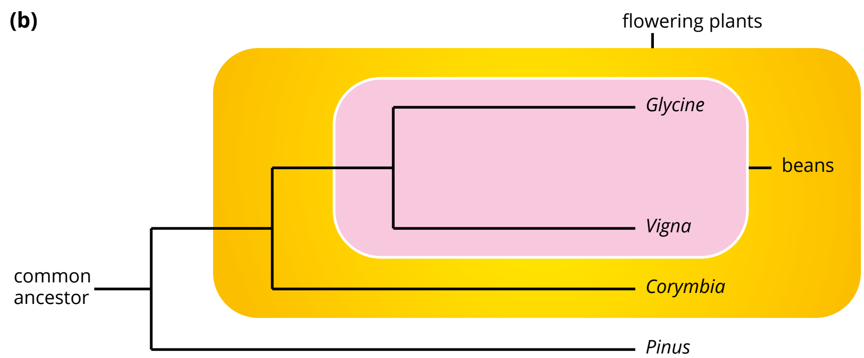


FIGURE 10.1.49 (a) Alignment of part of the sequence of the gene coding for ribosomal RNA (base positions numbered 1–11) of three flowering plants (a eucalypt, *Corymbia* and two beans, *Vigna* and *Glycine*) and a pine tree (*Pinus*). It shows that the three flowering plants have nucleotides in common (highlighted blue). Furthermore, the two beans have even more nucleotides in common (highlighted green), indicating their high similarity and close relationship. (b) The DNA sequence differences between the plant groups and their evolutionary relationships are represented in a phylogenetic tree.

10.1 Review

SUMMARY

Fossil evidence

- The fossil record is a catalogue of the occurrence and evolution of living organisms through geological time as inferred from fossils. It is not complete because the chance of a fossil forming is small.
- Palaeontology is the study of ancient life preserved in rocks and ancient sediments, including evidence of the structure of living organisms and how, where and when they lived.
- Fossils are the preserved remains, impressions or traces of organisms found in rocks, amber (fossilised tree sap), coal deposits, ice or soil. There are four main types:
  - impression fossils, left when the entire organism decays but the shape or impression of the external or internal surface remains
  - mineralised fossils occur when minerals replace the spaces in structures of organisms such as bones, and minerals may eventually replace the entire organism leaving a replica of the original fossil
  - trace fossils are preserved evidence of an animal's activity or behaviour, without containing parts of the organism (e.g. footprints)
  - mummified organisms are those that have been trapped in a substance and changed little.
- Dating of fossils can be determined by:
  - relative dating based on stratigraphy, which estimates a fossil's age by the known age of rock layers above and below the layer in which it is found
  - using index fossils, which are commonly found fossils from similar sites for which an absolute age has been determined
  - absolute dating using radiometric methods to measure the proportions of certain naturally occurring radioactive isotopes
  - absolute dating using thermoluminescence or electron spin resonance.
- Transitional fossils are any fossilised organisms that show intermediate traits and evidence of major change, such as animals moving from aquatic to terrestrial habitats.

Biogeography

- Biogeography is the study of the geographical distribution of organisms.
- The world is divided into a number of continental biogeographic regions and marine zones, each with a unique set of animals and plants.
- Some distribution patterns are best explained by continental drift theory (i.e that continents ride on crustal plates that gradually move).
- Geographic distributions and evolutionary age of organisms can be aligned with when landmasses separated.

Comparative anatomy

- Comparative anatomy is the study of the form and structure of organisms.
- Homologous features are those that have a fundamental similarity based on common ancestry, often evolved as different functions. These are evidence of evolutionary descent from a common ancestor (divergent evolution) into different organisms.
- Analogous features are those shared by different species that have the same function but have evolved separately due to similar selection pressures. Comparative anatomy can reveal that such features are structurally different (convergent evolution).
- A vestigial structure is a reduced structure with no apparent function, showing an evolutionary relationship.

Comparative embryology

- Comparative embryology studies the growth and development of a zygote to an adult organism.
- Embryonic comparisons show that general features of groups of organisms appear early in development. More specialised features, which distinguish the members of a group, appear later in development.

Biochemical evidence

- If two species have a similar set of proteins or DNA sequences, it is evidence that they shared a recent common ancestor.
- Changes in nucleotide sequences are caused by mutations, which accumulate throughout the genome over time.
- A mutation to a DNA sequence may not necessarily change the amino acid sequence because the genetic code is degenerate. However, as more differences in the nucleotide sequence of DNA occur due to mutations, more differences in the amino acid sequence occur.

10.1 Review *continued*

- Even when a point mutation leads to a change in amino acid, the mutation may not lead to a change in phenotype. This is called a conservative mutation and involves a change from one amino acid to a different amino acid with biochemically similar properties.
- A non-conservative mutation results in a change to a very different amino acid, which often leads to biochemical changes.
- Some genes accumulate mutations faster than others; conserved genes accumulate mutations slowly.
- Phylogenetic trees show the evolutionary relationship between different groups of organisms based on morphological and molecular similarities and differences.

KEY QUESTIONS

1 Describe what fossils are.

2 **a** What types of organisms or parts of organisms are most likely to be fossilised? Explain why.
b Describe some of the different ways in which organisms may be preserved relatively intact.
c Explain the difference between an impression fossil, a cast fossil and a trace fossil.

3 Define ‘biogeography’.

4 Define ‘continental drift’ and outline the biological evidence that supports this theory.

5 **a** What are homologous features?
b Use an example of an animal and an example of a plant to explain the significance of homologous features in terms of evidence of evolutionary relationships.

6 Clarify the difference between analogous features and homologous features. Describe an example.

7 **a** DNA sequences provide evidence of the evolution of organisms. Justify this statement.
b Explain how scientists can use DNA sequences to reconstruct the evolutionary history of species.
c Draw a phylogenetic tree to support your answer.

10.2 Recent evolutionary change

Charles Darwin believed that evolution is usually a gradual process. While it is sometimes, recent evidence points to this being unusual. Evolution normally proceeds in rapid bursts, potentially occurring within just a few years. This rapid evolutionary process is known as punctuated equilibrium and is covered in more detail in Chapter 9.

GO TO ➤ Section 9.1 page 388

In this section, you will learn about two case studies of recent, rapid evolution. These are cane toads and antibiotic resistance in bacteria.

CANE TOADS

In Chapter 7 you learnt about the highly adaptable cane toad (*Rhinella marina*) (Figure 10.2.2) and its invasion and population explosion in Australia since its introduction from Hawaii in 1935. In this section you will learn about the rapid evolution of the cane toad in Australia and the evolutionary responses of the native species it interacts with.

GO TO ➤ Section 7.3 page 334

The impact of cane toads in Australia

The cane toad continues to reproduce and spread at a rapid rate across Australia. Since their release, they have colonised a wide zone stretching from northern New South Wales to west of Darwin. The spread continues at an accelerating rate. Toads are projected to take over most of the northern half of Australia.

The cane toad was introduced to Australia as a biological control measure to save the sugar cane industry from cane beetles that were destroying crops. Cane toads showed little interest in cane beetles, but had a devastating effect on native wildlife. Toads consume many other water species, including insects, fish and reptiles. This also greatly reduced the amount of food available to native predators. Most importantly, toads have large poison glands on their backs. Often predators that eat toads die as a result. Native predator numbers have sharply declined everywhere toads have migrated. The toads have particularly affected Australia's reptiles.

Toads also devour dung beetles in large numbers. Dung beetles bury cattle dung. When dung beetles are unavailable, the dung piles up and affects cattle health. Thus cane toads also impact Australia's cattle industry.

FIGURE 10.2.2 The cane toad (*Rhinella marina*). Since its introduction to Australia, it has become a serious danger to native wildlife.

BIOFILE CCT

London mosquitoes

Mosquitoes that colonised the London Underground rail network when it opened in 1863 have since adapted to their new environment. Specifically, they developed a taste for human blood, whereas the ancestral type prefers birds' blood. The underground form also no longer hibernates. The two types are now so different, both in mating behaviour and reproductive biology, that they can no longer interbreed. Rapid speciation has taken place.

There has been continuing debate about the taxonomy and evolution of these mosquitoes. They diverged from *Culex pipiens* (Figure 10.2.1) and when first identified, they were named *Culex molestus* due to their vicious biting habits. Later they were placed back as a form of *Culex pipiens* called *Culex pipiens f. molestus*. Ongoing research from DNA and behavioural studies now identifies them as a separate species, called *Culex molestus*.

FIGURE 10.2.1 The London mosquito, *Culex pipiens*

Cane toad evolution

In less than a century, toad behaviour and phenotype has changed markedly. Cane toads are an example of modern-day rapid evolution.

The toads first introduced to Queensland were not especially active. Toads at the expansion frontier are different. Compared to their recent ancestors, frontier toads are larger (since large animals are faster), plus their legs are proportionally about 10% longer and stronger. The frontier toads' behaviour is different as well. Whereas ancestral toad populations move about 10 m/day, in no particular direction, frontier toads move 10 times that distance and in straight lines. Immediately after introduction, the area of toad distribution initially expanded by around 10 km/year. Now, the increase is around 60 km/year.

Over millions of years in their Amazon homeland, toads developed an ability to chemically detect the presence of their own species' eggs. If laying females sense the eggs of other individuals, they eat the eggs, clearing the water body for their own. Thus toads compete reproductively. Individuals able to escape the competition have an advantage. The new environmental context in Australia meant that speedy toads reproduced more successfully.

In what some researchers termed the 'Olympic Village effect', fast toads breed with other fast toads; in each generation the fastest offspring reproduce. This is an extreme example of selection pressure. It means that frontier toads are physically diverging from the core population at an unusually rapid rate.

The selection for speed only applies on the edge of toad territory. Toads deep within the species' range experience a different pressure. No matter how quickly they move, they cannot escape other toads, and speed offers no advantage. Those toads are thus relatively sedentary.

Once the main front catches up, the super-toads are disadvantaged. Many of the most robust individuals suffer from severe spinal arthritis in older age that restricts movement to short, slow hops. They also reproduce less. In that case, the selection pressure reverts to normal: the extreme phenotype is selected out, exaggerating the sharp difference between frontier and main-population toads.

While the divergence phenomenon lasts, it provides an unusual insight into evolutionary processes.

When organisms have a trait that gives a survival disadvantage, natural selection removes it. The trait is said to be **maladaptive**.

BIOLOGY IN ACTION S

Native wildlife fights back against the cane toad

Wherever cane toads have migrated in Australia, native wildlife has declined by up to 95%. Yet in an evolutionary response to the toads' presence, some of the wildlife is bouncing back.

Certain effects are indirect. For instance, the black-headed python, once rare across northern Australia, is now numerous. The probable reason is that goannas, predators of python eggs, often fall victim to toads (Figure 10.2.3). Without goannas, the pythons thrive.

Yet other effects are directly evolutionary. Until the arrival of cane toads, red-bellied black snakes (Figure 10.2.4) in New South Wales and Queensland formed a single population. Yet after more than 80 years of co-existence with toads, the Queensland snakes' heads and mouths have become smaller. Toad toxicity is proportional to size; larger toads contain more toxin. Thus a small-headed snake only able to eat small toads will be exposed to less toxin. Such snakes are more likely to survive the encounter than snakes able to eat large toads. The presence of toads provides a clear selection pressure towards smaller heads, to which southern snakes are not exposed. In the same way, the Queensland snakes have become more able to digestively neutralise toad venom than NSW relatives.

Some of the response is learnt. Certain individual predators, including tree snakes and native frogs, avoid toads completely. In humans, a severe bout of food poisoning makes the sufferer avoid whatever caused the poisoning for the rest of their lives. The same may be true among native predators. Researchers plan to actively train predators, such as quolls (Figure 10.2.5), to avoid cane toads.

FIGURE 10.2.3 (a) The black-headed python (*Aspidites melanocephalus*). (b) The lace monitor (goanna) (*Varanus varius)* is a predator of the black-headed python's eggs.

FIGURE 10.2.4 The red-bellied black snake (*Pseudechis porphyriacus)* in Queensland has evolved a smaller head and cannot eat the most deadly cane toads.

FIGURE 10.2.5 The northern quoll (*Dasyurus hallucatus)* is vulnerable to cane toad poison but could possibly be trained to avoid eating them.

In addition, predators that do eat toads have developed safe strategies for handing them. For example, Torresian crows and black kites (Figure 10.2.6) have separately learnt to kill toads by flipping them on their backs and attacking their non-poisonous undersides. Also, some Australian dwarf crocodiles only eat the toads' hind legs. Doing so provides these predators with a plentiful food source at no risk, thus they are likely to prosper from the toads' presence.

If such behaviours have a genetic basis (and in animals, behaviour often does), individuals possessing the traits will pass on their advantageous alleles. Subsequent generations of Australian predators will evolve to co-exist with the toads, via a combination of adaptations.

The native wildlife may regain, if not surpass, its former abundance. Queensland's goannas and dwarf crocodiles are already recovering.

FIGURE 10.2.6 The black kite (*Milvus migrans)* has learnt to flip cane toads onto their back and only eat the non-toxic underbelly.

ANTIBIOTIC RESISTANCE

FIGURE 10.2.7 Common types of human skin bacteria, including *Streptococcus* sp. and *Staphylococcus* sp. (spheres), *Escherichia* sp. and *Bacillus* sp. (rods), *Leptospira* sp. and *Spirillum* sp. (spirals), plus *Vibrio* sp. Over 120 different types of bacteria normally inhabit human skin. (Coloured SEM)

Bacteria is literally all around us (Figure 10.2.7). We co-exist with some species. Gut bacteria, for example, are essential for food digestion and we could not live without them. Yet those or other species cause harm if they enter other parts of the body, whether via wounds, unhygienic surgery, inhalation or other means. The **infection** causes an **immune response**. That is when the body's defences, particularly white blood cells, attack the foreign cells.

Normally our immune systems cope with minor infections. However, in cases of weakened immunity or extensive infection, our immune systems cannot cope. Throughout human history, severe infections usually proved fatal. The bacteria's exponential growth (increasing rapidly at a nonlinear rate) overwhelms our immunity.

This changed from the 1940s, with the development of **antibiotics**. These are drugs that disrupt bacterial reproduction without effect on human cells. With the exponential reproduction halted, our immune systems can easily deal with the infection. The drugs have saved at least 200 million lives that otherwise would have been lost to infection.

The active ingredients of antibiotics are naturally occurring compounds, evolved by various kinds of organisms as defence against bacterial infection (Figure 10.2.8). Countless such compounds exist in nature. Yet so far only around 100 antibiotic drugs have been developed, falling into seven main classes.

However, just a few years after first being introduced, antibiotics had stopped working in certain cases. The target bacteria evolved **resistance**. Antibiotic resistance is now a serious international health concern.

Evolved resistance

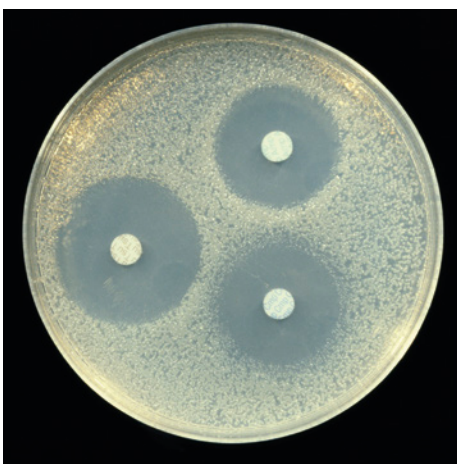


FIGURE 10.2.8 A dish containing typhoid bacteria *(Salmonella typhi)*, which causes typhoid fever. The white circles are three different antibiotic substances, surrounded by zones of exclusion into which the bacteria cannot grow due to the presence of the antibiotic.

The genetics of bacterial variation is both simpler and more complex than for more advanced organisms. It is simpler because bacteria reproduce asexually. Bacteria do not shuffle two sets of parental genes during **meiosis** (cell division). Each **bacterium** has only one parent, of which subsequent generations are nearly perfect clones. Mutation is one of few sources of genetic variation. Yet the situation is also complex because bacteria (and most other microbes) are capable of **horizontal gene-transfer**. This means that any microbe can transfer genes to any other. In this way, bacteria can rapidly acquire tremendous genetic variation and new traits from unrelated species. The greater the variation, the more natural selection has to work with, and the more adaptable a species will be. Because bacteria can reproduce so rapidly, one bacterium quickly becomes two, two become four, four become eight, and so on. Bacterial populations can double in 4 to 20 minutes, giving them the ability to form millions of cells in as little as a few hours. This rapid rate of reproduction means that bacteria can also rapidly evolve.

Natural selection works the same way for all organisms. Individuals most suited to their environment survive to reproduce, whereas the less fit reproduce less or not at all. Selection for certain traits means preservation of the underlying alleles for that trait. The proportion of the population carrying alleles for advantageous traits increases over successive generations.

In practice, each antibiotic prevented reproduction in most bacteria but not all. By chance, some were naturally resistant. The unaffected few passed on their alleles for resistance to subsequent generations. Survivors may also have acquired alleles for resistant traits from other species. Through many generations, the most effective combination of alleles for resistance increased in the population.

In other words, bacteria evolve, and at tremendous speed. Drugs that once reliably inhibited bacteria's exponential reproduction rapidly become ineffective. New bacterial strains continue to emerge, evolving resistance to new treatments as they are discovered and introduced to the human population.

The current crisis

Although many antibiotics still work, many others do not. Because of evolved resistance, some forms of infection now require multiple antibiotics in combination. Many infections are becoming less treatable or untreatable in some cases. People are again dying of infection, and the problem will continue to worsen.

The situation arose from widespread misuse of the drugs. A major cause was use of low-dose antibiotics in livestock feed. Modern factory-farming methods put animals into unnaturally close contact in unhygienic conditions where disease is common (Figure 10.2.9). Using antibiotics in food prevents low-level infections that would slow animals' growth and lower financial returns. In the USA, livestock feed accounts for 80% of antibiotic usage. Continual weak doses are a perfect way to cultivate resistant bacterial strains.

FIGURE 10.2.9 Intensively farmed chickens are kept in stressful and unsanitary conditions. Use of antibiotics in animal feed helps prevent infections that might slow growth, although the practice is also a major cause of antibiotic resistance.

A second major cause has been physicians inappropriately prescribing antibiotics for human patients (Figure 10.2.10). Many antibiotic prescriptions are unwarranted. A common situation is patients requesting or being given antibiotics for cold symptoms, although antibiotics have no effect on viral infections. In other cases, patients often either do not finish the full course of antibiotics, or continue taking the drugs for too long. Short, high-dose applications are most effective.

FIGURE 10.2.10 Medical practitioners are another key factor in antibiotic resistance. Doctors often prescribe antibiotics for viral infections such as colds or influenza, even though these medicines have no effect on such conditions.

Many of the world's leading medical authorities agree that a crisis is imminent. Solutions may involve the development of new drugs plus tighter guidelines on usage.

Misuse has undoubtedly accelerated antibiotic resistance. However, the problem would have eventually arisen anyway. Bacteria and other life forms have been locked in an evolutionary arms race for billions of years. Every time one side develops a new weapon, the other adapts.

Therefore, there can never be any single, permanent solution. We must understand that evolution is a constant fact of life. Thus each drug has a limited useful lifespan; every new introduction must include plans for its replacement.

Bacteria make it easy to appreciate evolution: in them we can literally watch it happening.

Antibiotics have no effect on viral illnesses such as colds. Taking antibiotics for these conditions accelerates the evolution of antibiotic-resistant bacteria.

BIOLOGY IN ACTION CCT PSC

The return of infection

In September 2016, an unnamed elderly American woman died in a Nevada hospital.

The woman had contracted a 'superbug' infection. Each of 26 different powerful antibiotics, used in combination, failed to control the infection. Doctors later stated that no drug then available in the United States could have saved the woman's life.

The woman had spent considerable time in India. She broke her femur (thigh bone) there and later developed a bone infection at the break point. The infection involved a bacterial species normally resident in the gut. In India, both multi-drug-resistant bacteria and unhygienic water are serious problems. The woman contracted the infection from either contaminated water or an Indian hospital.

Although the infection did not spread in this case, it easily could have. Widespread exposure to multi-drug-resistant bacteria would constitute a public-health catastrophe.

Although more strains of multi-drug resistant bacteria will inevitably evolve, doctors will be even less able to combat them. Some major drug companies have reduced their antibiotic research programs because of high costs and perceived low profits. Although some smaller companies continue development, the work takes many years. Furthermore, new drugs will make little difference unless we collectively change our patterns of usage (Figure 10.2.11).

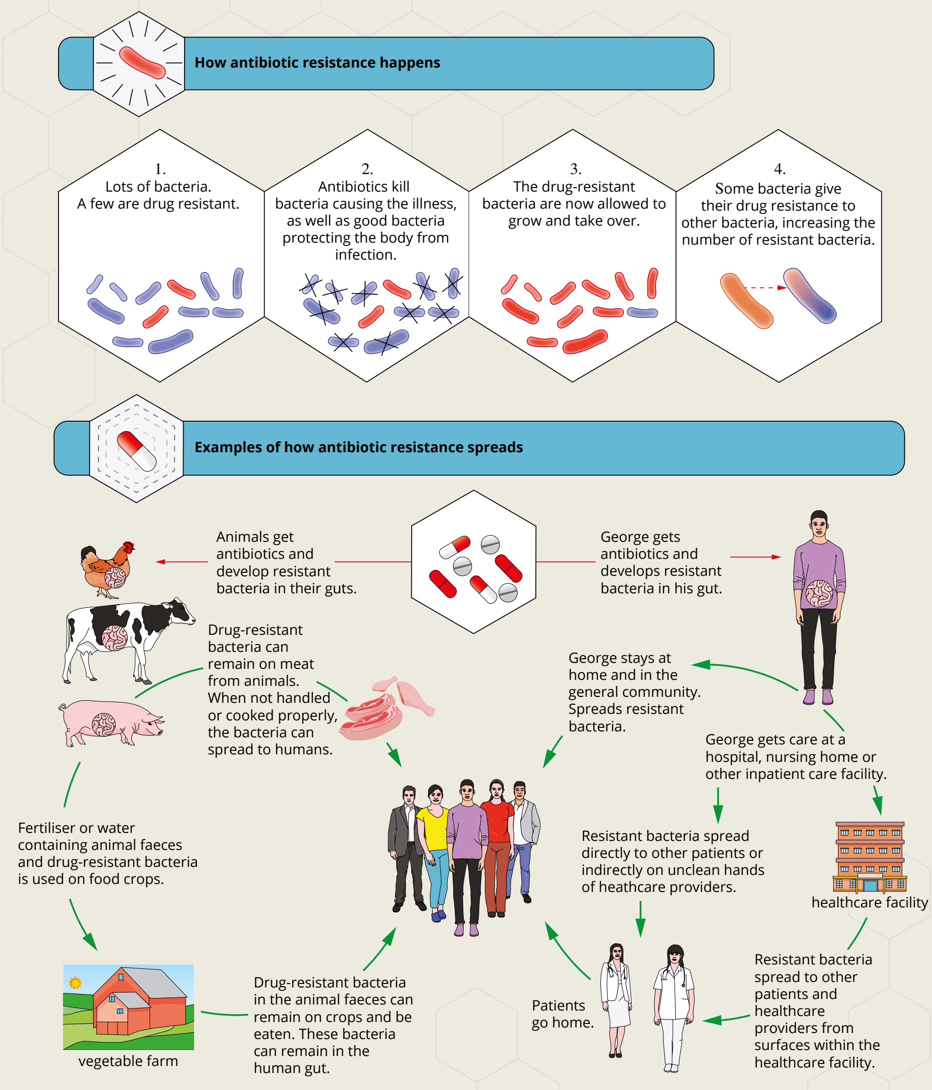


FIGURE 10.2.11 Infections that were once successfully treated with antibiotics are now becoming serious health problems due to antibiotic resistance. The evolution and spread of antibiotic resistance is accelerated by the overuse of antibiotics in agriculture and misuse of antibiotics in the human population.

BIOLOGY IN ACTION CC

Lord Howard Florey

The person who made antibiotics into a practical medicine was an Australian scientist, Howard Florey (Figure 10.2.12). Born in Adelaide, where he studied medicine, Florey then won a Rhodes scholarship to Oxford University, and completed a doctorate at Cambridge. As professor of pathology (disease) from 1935, he worked at several prestigious British institutions including Oxford.

Starting in 1938, Florey gathered an expert team to study antibacterial substances found in moulds. A paper by British scientist Alexander Flemming alerted the team to penicillin, a compound found in the *Penicillium* mould (Figure 10.2.13). Although Flemming discovered the compound, Florey and team made it work.

FIGURE 10.2.12 Professor Howard Florey (1898-1968), Australian pathologist. Florey was co-recipient of the 1945 Nobel Prize for Medicine for his work on penicillin.

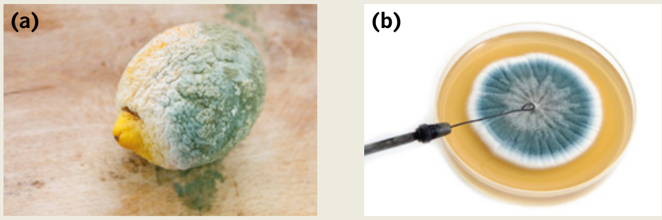


FIGURE 10.2.13 (a) *Penicillium* sp. fungus growing on a lemon, showing the fine hyphae filaments (white) and spores (green). (b) A culture of the same fungus in a Petri dish. The *Penicillium* mould produces the antibiotic known as penicillin.

The first breakthrough was a test on mice infected with a deadly dose of *Streptococcus*. After one day, the control mice had died but the treated group had completely recovered.

Albert Alexander was the first human patient. He had picked up a serious facial infection from a rose-thorn scratch. Treated with penicillin, he immediately began to recover. However, he later relapsed and died because Florey's team did not have enough of the medicine.

Under extremely difficult wartime conditions, Florey's team prepared the drug using whatever was available. They used hospital bedpans to grow mould, and filtered the liquid through parachute silk.

British companies were unable to help with the manufacture. However, Florey got a United States Department of Agriculture laboratory involved. That yielded an abundant new growth medium for the mould (a corn byproduct), and a tenfold increase in production.

During 1943, Florey tested penicillin on wounded soldiers with spectacular results. By the end of the war, penicillin was available to allied troops (Figure 10.2.14). Australia was the first country to make the drug available for civilian use. Many companies started manufacturing it commercially.

However, several penicillin-resistant bacterial strains emerged almost straight away. During the 1950s, scientists created artificial penicillin by chemically changing the natural compound. That delayed evolved resistance for a while.

Florey was knighted in 1944, and shared the Nobel Prize in 1945. He also received a long list of other highly prestigious awards. Despite becoming a baron in 1955, he did not share in the commercial benefit from his work. In those days, the patenting of medicines was considered unethical.

Florey was highly instrumental in the formation of the Australian National University (ANU). Although residing in Oxford, Florey was effectively the first head of the ANU's John Curtin School of Medical Research. Approximately 10 km from the school, the Canberra suburb named after him honours Howard Florey's legacy.

FIGURE 10.2.14 Penicillin drug treatment, World War II, at the US Army's 142nd General Hospital

10.2 Review

SUMMARY

- Evolution often proceeds rapidly. There are many known examples of evolution occurring within just decades.
- The cane toad has rapidly evolved since its introduction to Australia. Reproductive competition and a new environment involve selection pressures that have favoured the fastest, strongest toads.
- Cane toads at the edge of the species' range are physically and behaviourally different—they are larger and faster, with proportionally stronger legs, and travel more directly, enabling them to rapidly invade new environments. Frontier toads are diverging from the main population because of differing selection pressures in their new environments. Cane toads have evolved these new adaptations in less than 80 years.
- The rapid evolution observed in the cane toad may be temporary. Once the main population catches up to the frontier population, fast toads are reproductively disadvantaged. Where adaptations for speed and strength are not advantageous, selection pressures may lead to a reduction in these toads and slow their evolution.
- The toxicity of cane toads has caused an evolutionary response in some species of native wildlife, including physical and behavioural changes.
- The presence of bacteria inside human tissues causes an immune response. Often this response is insufficient to deal with bacterial exponential growth, leading to death by infection.
- Antibiotics are naturally occurring substances that inhibit bacterial reproduction. When used as human medicine, antibiotics allow the immune system to regain the upper hand.
- Penicillin was the first human antibiotic, derived from the *Penicillium* mould.
- After the introduction of antibiotics during the 1940s, the drugs soon became ineffective due to evolved resistance. Evolved resistance is a case of rapid evolution by natural selection.
- Misuse of antibiotics in animal feed and as human medicines has accelerated evolved resistance.
- Bacteria can develop new traits via mutation, and via horizontal gene-transfer with other microbes. Bacteria reproduce at an exponential rate and can quickly acquire and pass on alleles for resistance, leading to the evolution of new resistant strains.
- Antibiotic resistance means that infection is becoming more difficult to treat. There can never be a permanent solution, only solutions that address the fact of rapid bacterial evolution.

KEY QUESTIONS

1 Species always evolve at a constant, slow rate. Is this statement true or false? Give reasons for your answer.

2 Identify two examples of evolution that have occurred within recent times.

3 **a** Summarise the evolutionary changes that have occurred in cane toads since their release in Australia.

b Explain these changes in terms of natural selection.

4 Cane toads in Australia represent an example of divergent evolution. Is this statement true or false?

5 Define the term 'infection'.

6 What are antibiotics?

7 Explain the evolution of antibiotic resistance.

Chapter review

10

KEY TERMS

absolute dating
allele
amino acid
analogous feature
antibiotic
bacterium (pl. bacteria)
biochemical
biogeographic region
biogeography
chromatid
chromosome
codon
common ancestor
comparative anatomy
comparative embryology
conservative substitution
continental drift
convergent evolution
developmental biology
divergent evolution
DNA sequence
embryo
fossil
fossil record
fossilisation
genome
half-life
homologous feature
horizontal gene-transfer
immune response
impression fossil
index fossil
infection
isotope
maladaptive
meiosis
mineralisation
mineralised fossil
mitochondrial DNA
mitosis
molecular
molecular clock
morphology
mummified organism
mutation
mutation rate
non-conservative substitution
nucleotide
palaeontology
petrification
phylogenetic
point mutation
relative dating
resistance
semi-conservative substitution
stratigraphy
stratum (pl. strata)
trace fossil
vestigial structure
zygote

REVIEW QUESTIONS

1 How are fossils valuable to palaeontologists?

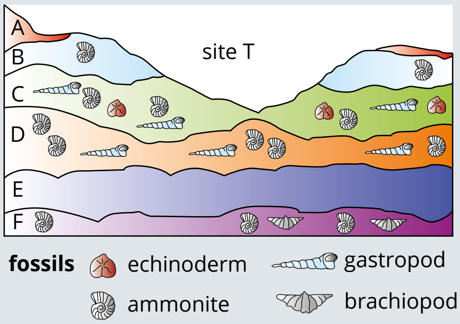
2 **a** What are the four types of fossil?
b How would each have formed?

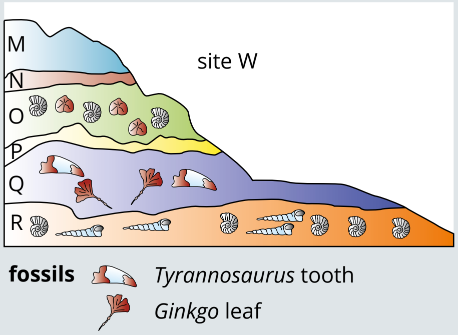
3 All periods of life on Earth are represented by fossils equally. Is this statement true or false? Explain your answer.

4 Most organisms that die become fossils. Is this statement true or false? Explain your answer.

5 Explain thermoluminescence and its application in palaeontology.

Use the following diagrams to answer Questions 6 and 7.



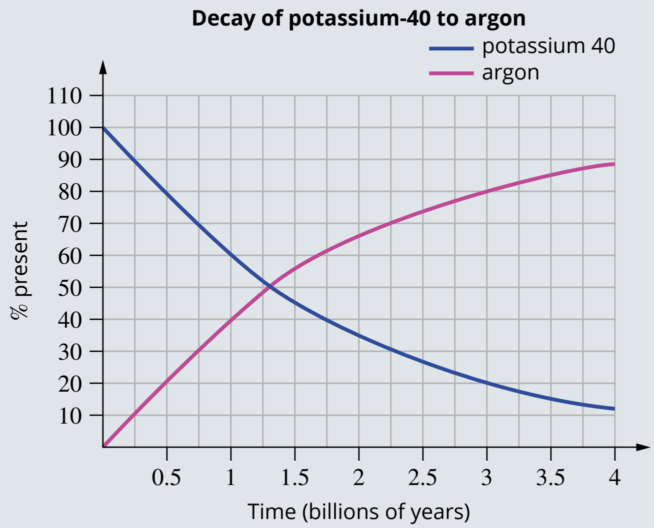


6 Fossils are found in sedimentary rocks. Barring major tectonic upheavals, it can be assumed that the layers have been laid down in order, with the oldest on the bottom.
One method of dating the layers of rock is to use index fossils (also called indicator fossils).
a **i** Which of the fossils observed at site T has the potential to be a good index fossil?
ii Explain your choice.
b Consider the two sites.
i Which layer is the most ancient?
ii How do you know?
c Stratum E at site T is sedimentary but there is no evidence that it contains any fossils. Why might there have been no fossils found in that stratum?
d At site W, stratum R contains ammonites and gastropods while stratum Q contains *Tyrannosaurus* teeth and *Ginkgo*. What does this suggest about the respective environments?

7 A method of absolute dating used for rock strata is radioactive dating. This method can only be used for igneous rocks. In order to date rocks by this method the amounts of a radioactive material in the rock and the decay products are measured. First the half-life for the radioactive material must be calculated.
a **i** What is a half-life?
ii One radioactive material (the parent) and its decay product (the daughter) used for this sort of dating is shown in the graph below. What is another radioactive material and its daughter?

iii A decay curve is generated for the radioactive material in order to determine the age of the rock. Use the graph to determine the half-life of potassium-40 (^{40}K).

b The rocks in strata N and P at site W were determined to be igneous in nature. They were both analysed to determine the percentage of ^{40}K left in the rock.



Use the graph to determine the age of the two strata if the rocks of:

i stratum N contains 90% ^{40}K

ii stratum P contains 75% ^{40}K.

c What is the likely age of stratum O?

8 **a** For each of the following fossils identify whether ^{14}C dating would be a suitable method to obtain an absolute date for the fossil.

i an insect preserved in amber that formed sometime during the Palaeogene

ii a dinosaur footprint

iii a hand axe used by a member of *Homo neanderthalensis* during the last days before they became extinct

iv an Egyptian mummy

b For each fossil for which ^{14}C dating is not suitable, explain why.

9 Suggest some reasons why the fossil record is incomplete.

10 Cane toads (*Rhinella marina*) were introduced into Australia in the 1930s to eat cane beetles that attacked sugar cane in central and northern Queensland. This introduction has proved to be an ecological disaster. The toads did not eat the beetles, but ate many small native animals, including frogs and small mammals, and native predators that eat the cane toads frequently die because cane toads produce a very toxic chemical in their skin.

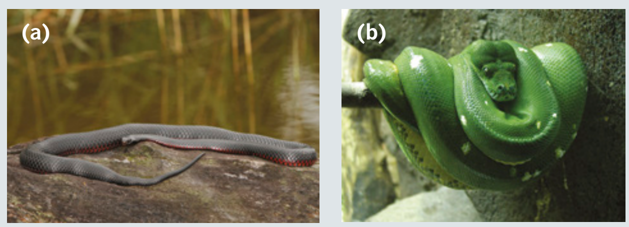
Cane toads are large. On average their bodies are over 10 cm in length (not including limbs) and they can weigh in excess of 160 g.

Researchers assessing the ecosystems that have been invaded by the fast-spreading toads have noticed an interesting phenomenon in some snakes. Snakes commonly feed on frogs and toads. Two species of snake are particularly susceptible to cane toad poison, the red-bellied black snake (*Pseudechis porphyriacus*) (Figure a) and the green tree snake (*Dendrelaphis punctulatus*) (Figure b). The researchers have observed that in areas invaded by cane toads the populations of both of these snakes are showing an average increase in body size and decrease in mouth gape (how wide the mouth can be opened).

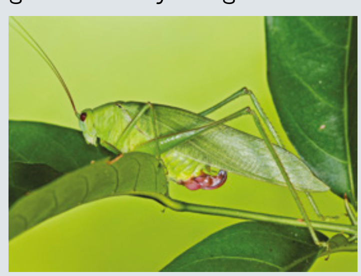
Snakes have a generational time of about 3 years so between 20 and 25 generations would have occurred since the introduction of the toads.

a Suggest how larger body size and smaller mouths could be an advantage in an environment containing cane toads.

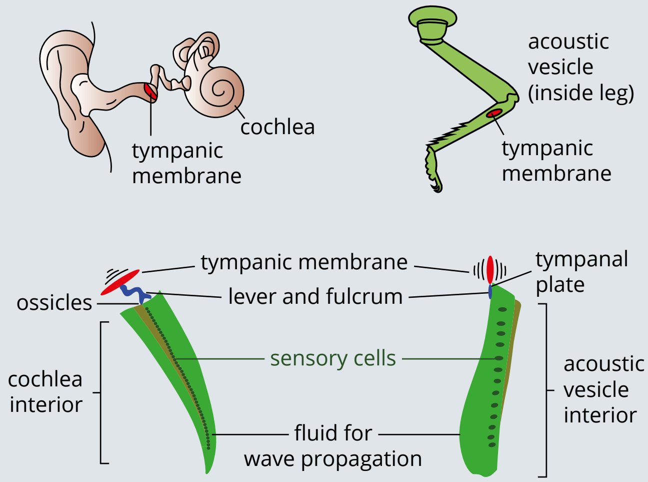
b Is this an example of natural selection? Explain your reasoning.



11 Katydids (also known as bush crickets) are a large group of insects found across the world. There are over 6400 known species grouped into nearly 50 genera, which belong to the family Tettigoniidae.



Researchers in South America were investigating hearing in an endemic species of katydid. They found that this particular species has solved the hearing problem in a very interesting manner. The katydid has its hearing organ on its legs. The hearing organ has an outer membrane attached to a stiff inner structure that vibrates in time with the outer membrane. The stiff structure taps on a fluid-filled chamber, which is lined with sensory cells that sense the vibrations and pass the information to the brain of the insect.

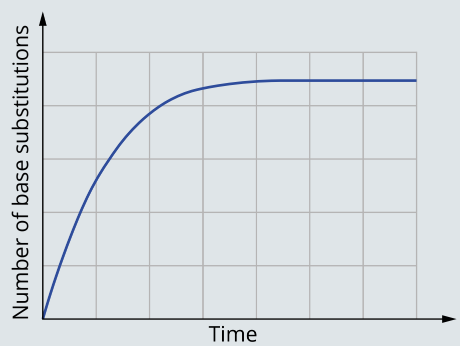


a Hearing in mammals and katydids is achieved using similar processes, despite the fact that the structures involved are not considered to be homologous. Explain why.

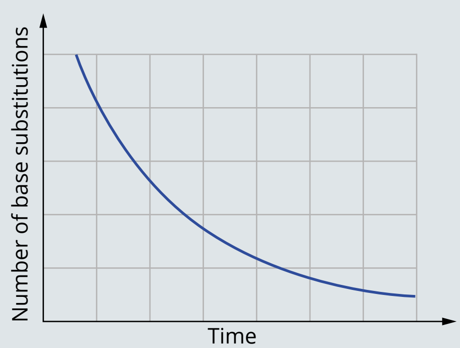
b What type of evolution is being shown in this situation? Explain your reasoning.

12 Which graph would best illustrate the assumed rate of the molecular clock?

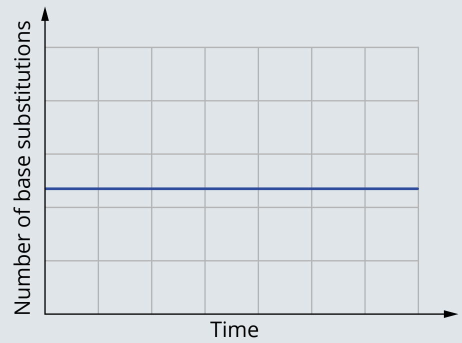
A



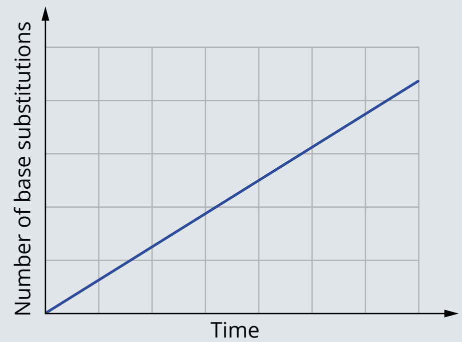
B



C



D

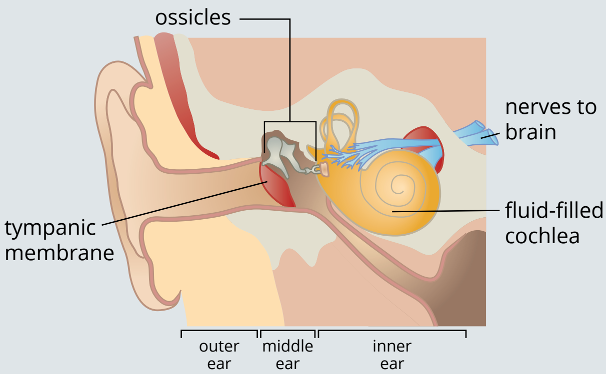


13 It has been established that human mitochondrial DNA is maternally inherited. Using this understanding, scientists have postulated that all living humans are related to a single female (Mitochondrial Eve), who lived between 140 000 and 200 000 years ago. There is a general misconception that this means that all humans are descended from only one female. Explain why this interpretation is incorrect.

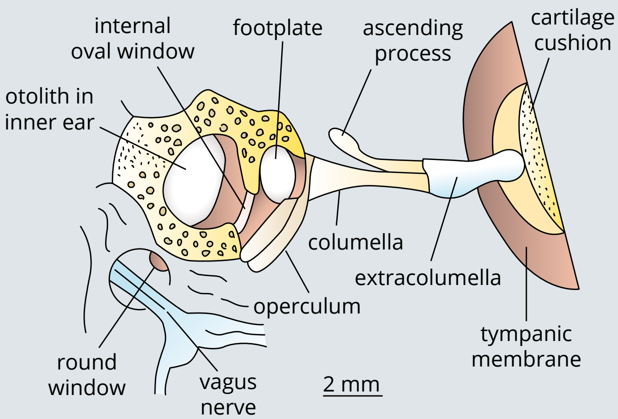
14 Hearing is quite a complex process. In humans and other mammals, it involves an outer membrane (the tympanic membrane or eardrum) and three bones (incus, malleus and stapes), also known as the auditory ossicles. The ear bones can transfer vibrations from the tympanic membrane to an inner fluid-filled chamber called the cochlea.

The cochlea is lined with sensors that detect the vibrations in the fluid and transfer the information, via nerve signals, to the brain.

The mammalian incus and malleus evolved from parts of the jaw of fish and the stapes evolved from the hyomandibula bone. In fish this bone helps to support the gills.



Reptiles have a single bone, the columella, which evolved from the hyomandibula bone. The columella transfers the sound from the tympanic membrane to the fluid-filled inner ear.



Explain whether the bones of the middle ear in mammals and reptiles are homologous or analogous.

15 What are vestigial structures? Give an example.

16 Identify the following as analogous or homologous features.

a the wings of butterflies and the wings of birds

b the flippers of whales and the fins of fishes

c the arms of humans and the flippers of seals

17 Outline how comparative embryology provides evidence for evolution. Give an example.

18 Which of the following species has accumulated the most mutations from the ancestral sequence: CAATTATCG?

A CATTTATCG

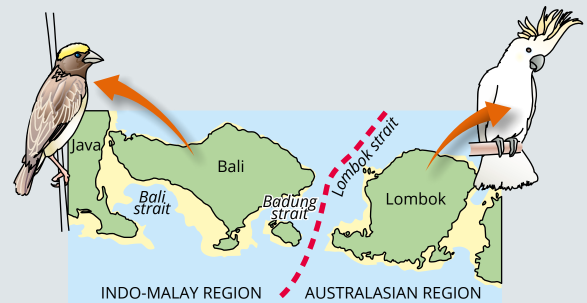
B CAAATAACG

C CTATTTACG

D CATTTGTGC

19 a What observations led Alfred Russel Wallace to map the biogeographic boundary known as Wallace's line?

b Why does Australian wildlife live to the east of Wallace's line, but to the west the wildlife is Eurasian?



20 What will happen to the divergent form of cane toads once the species has occupied its entire potential range in Australia (i.e. can expand no further)?

21 Suggest a reason why antibiotic compounds evolve in nature.

22 How do antibiotics control bacteria?

23 *Staphylococcus aureus*, also known as 'golden staph', is a species of bacteria responsible for serious illness in humans. Symptoms include skin rash, aches and pains, fever, boils and ulcers. Complications of *S. aureus* infections can result in limb amputations and even death. *S. aureus* is very contagious, and is easily passed from person to person through skin contact. Hospitals regularly report outbreaks of this infection, which is usually treated effectively with a course of the antibiotic methicillin. In 1996 a child in Japan diagnosed with a *S. aureus* infection failed to recover. He was diagnosed as suffering from methicillin-resistant *S. aureus* (MRSA). He was subsequently treated with the more potent antibiotic vancomycin, but again with no success. Finally, the child was prescribed an experimental antibiotic, arbekacin, and eventually recovered.

a Suggest why *S. aureus* is relatively common in hospitals.

b Describe the steps that have resulted in the population of vancomycin-resistant bacteria.

c Outline one advantage and one disadvantage of developing more and more potent antibiotics.

24 What are the broad social and medical consequences of evolved antibiotic resistance?

25 Name two contributing factors to the current crisis of evolved antibiotic resistance.

26 Can evolved antibiotic resistance be prevented in the future? Explain your answer.

27 After completing the Biology Inquiry on page 438, reflect on the inquiry question: What is the evidence that supports the theory of evolution by natural selection? Recall at least three examples of evidence that demonstrate rapid, recent evolutionary change.

MODULE 3 • REVIEW

REVIEW QUESTIONS

Biological diversity

WS 3.8 WS 3.9 MR 3

Multiple choice

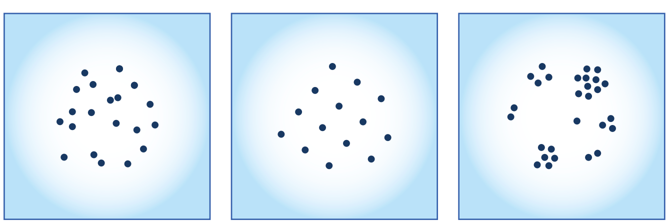
1 Selection pressures are all the biotic and abiotic factors in an organism's environment which affect the individual's behavior, survival and reproduction. Which list contains two abiotic and two biotic factors that act as selection pressures on koalas in the wild?

A rainfall, salinity, humans, grass
B eucalyptus tree, fire, soil pH, soil minerals
C soil temperature, oxygen, eagle, water
D air temperature, light, eucalyptus tree, goanna

2 Identify the list with biological levels organised from the smallest to largest grouping of organisms.

A individual, community, biome, population, ecosystem, biosphere
B individual, population, community, ecosystem, biome, biosphere
C individual, population, ecosystem, community, biome, biosphere
D individual, community, population, ecosystem, biome, biosphere

3 The three diagrams below represent distribution patterns for populations of organisms. Which choice (A, B, C or D) has them listed correctly?

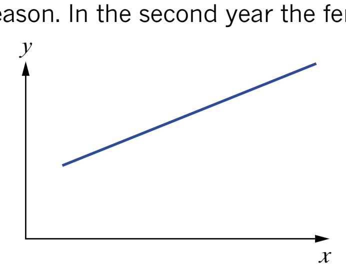


A A = uniform, B = random, C = clumped
B A = clumped, B = uniform, C = random
C A = random, B = uniform, C = clumped
D A = clumped, B = uniform, C = clumped

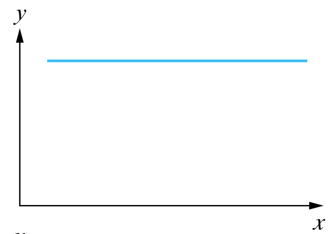
4 Which of the graphs below describes the following observation?

A small population of rabbits moves onto a farm grazing paddock after the rabbit-proof fence around it is damaged. In the first year there is a good breeding season. In the second year the fence has been repaired.

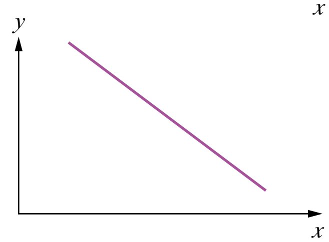
A



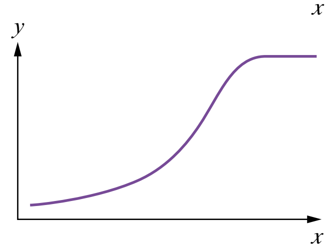
B



C



D



5 Four adaptations of the Australian red kangaroo are:

i a dense network of blood vessels close to the skin in the forelimbs
ii licking the forelimbs in hot weather
iii a powerful tail that acts as a counterbalance when hopping
iv the blood vessels in the forelimbs widen (dilate) in hot weather.

Which one of the following groups correctly classifies these four adaptations?

A i = physiological, ii = behavioural, iii = structural, iv = physiological
B i = structural, ii = behavioural, iii = structural, iv = physiological
C i = structural, ii = behavioural, iii = structural, iv = behavioural
D i = physiological, ii = behavioural, iii = physiological, iv = structural

6 In Australia, prickly pear and cane toads are both introduced species that have undergone population explosions and have extensive distributions. What is the current status of each?

A Both are still increasing in distribution and abundance.
B Prickly pear has decreased in distribution and abundance; cane toads are still increasing for both.
C Prickly pear is still increasing in distribution and abundance; cane toads have decreased for both.
D Both have been controlled and are decreasing in distribution and abundance.

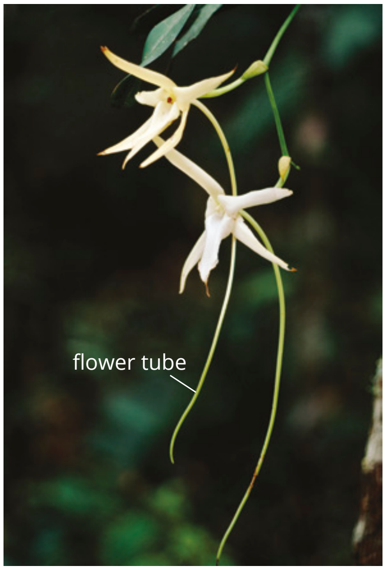
7 Which group (A, B, C or D) has the adaptations classified correctly?

	Structural	Physiological	Behavioural/ movement
A	blubber layer	CAM photosynthesis in plants	tropisms in plants
B	frost tolerance	small ears	sunken stomata
C	rolled leaves	hibernation	salinity regulation in plants
D	webbed feet	feathers	camouflage markings

8 Evaporative cooling techniques can be physiological or behavioural adaptations. In which choice (A, B, C or D) are they identified correctly?

	Physiological	Behavioural
A	gular fluttering	nocturnal activity
B	sweating	panting
C	huddling	licking skin
D	wallowing	seeking shade

9 A species of moth known as Morgan's sphinx moth (*Xanthopan morganii*) has an extremely long tongue that has evolved over many thousands of generations. This moth exploits a food resource unavailable to other moths. It uses its long tongue to collect nectar from the flower of a plant called Darwin's orchid (*Angraecum* sp.). This plant has a very tubular flower so only the long tongue of the moth can reach the nectar. In the process of collecting the nectar the moth collects pollen and then it carries it to other orchids, which it pollinates. Over time both the flower tubes and the moth tongues have become longer.



This relationship between the moth and the orchid is best described as an example of:

A natural selection
B allopatric speciation
C coevolution
D convergent evolution

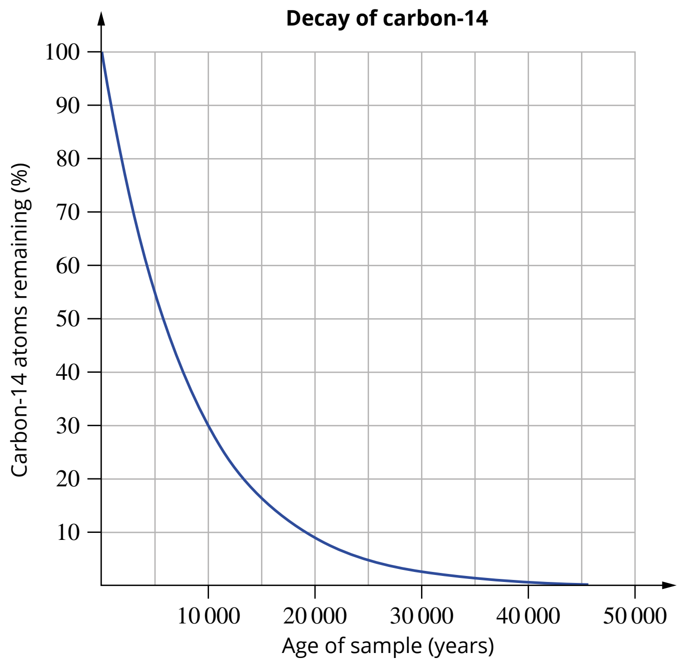
10 There are two wild species of banana: *Musa acuminata* and *Musa balbisiana*. Today there are many varieties of this popular fruit. These original wild varieties have 22 chromosomes. The most popular variety of bananas grown in Australia today is the Cavendish. It accounts for more than 95% of all production. Cavendish bananas have been around since before 1850. The Cavendish banana has a chromosome count of 33. The development of this variety of banana is most likely due to:

A polyploidy
B hybridisation between *Musa acuminata* and *Musa balbisiana*
C genetic engineering
D self-fertilisation by a member of *Musa acuminata*

11 Mass extinction events have been a feature of Earth's biological history. The largest of these extinction events is known from fossil evidence to have occurred at the end of which period?

A Devonian
B Ordovician
C Cretaceous
D Permian

12 Radioactive dating methods are frequently used to give absolute dates to fossils. One radioactive dating method used to date fossils directly uses the carbon-14 isotope. The graph below shows the decay of carbon-14 to nitrogen-14.



A fossil is found which has 60% carbon-14 remaining. What is the approximate age of the fossil?

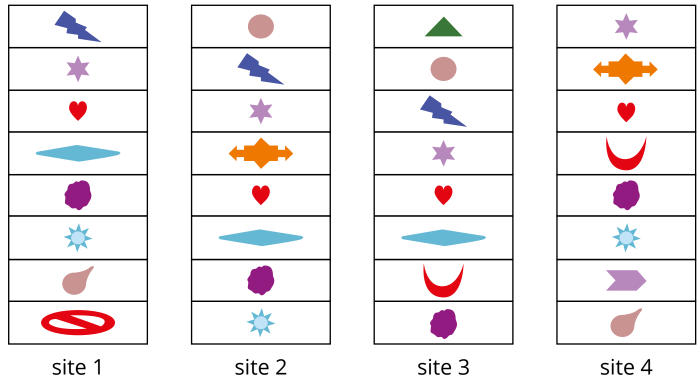
A 10 000 years
B 8000 years
C 6000 years
D 4000 years

13 A molecular clock is used to measure the rate of evolutionary change in a group of related organisms. The molecular clock uses the known mutation rate of genes shared by the organisms under investigation to estimate when they diverged from each other. This information is then used to construct scaled evolutionary (phylogenetic) trees. To be used as a molecular clock a gene needs several features.

Which of these is the most important feature?

A It has a recent origin.
B It is being acted upon by a strong selection pressure.
C It is positioned close to a telomere.
D It has a constant mutation rate.

14 Stratigraphic correlation is used to work out the relative ages of sedimentary strata (rock layers) at different sites. Strata containing the same index fossils are assumed to be the same age. It is also assumed that lower layers are older than upper layers.



Consider the four sites represented in the diagram. Which one of the following statements is accurate?

A Site 3 contains the youngest stratum and site 4 the oldest.
B Site 1 contains both the youngest and the oldest strata.
C All strata at the same depth are the same age.
D Site 1 contains the oldest stratum and site 3 the youngest.

15 Identify the statement that is most accurate for the relationship between evolution and natural selection.

A Natural selection is the mechanism for evolution.
B Evolution is the mechanism for natural selection.
C Evolution results in natural selection.
D Natural selection results in evolution.

16 Which of the following is an example of evolution by natural selection?

A genetically modified soybean crops
B breeding drought-resistant cattle
C antibiotic-resistant strains of bacteria
D bacteria that produce human insulin

17 Select the statement that describes punctuated equilibrium.

A Organisms undergo continuous, slow and gradual evolutionary change over time.
B Organisms stay quite stable in form until selection pressures cause relatively rapid evolutionary change.
C Organisms become extinct when they are not in balance with their environment.
D Organisms have regular cycles of rapid evolutionary change followed by periods of stability.

MODULE 3 • REVIEW

18 Many fossils have been found around the world that can reliably be identified as marsupials due to their distinctive pelvic bone structure. These fossils provide evidence for which of the following?

- **A** Marsupials originated in Australia and have always been unique to this continent.
- **B** Marsupials have only ever lived in Australia and South America.
- **C** Marsupials in Australia and South America have analogous features.
- **D** Marsupials and their ancestors have migrated across many landmasses over Earth's history.

19 Identify a change that has occurred in the distribution of Australian flora and fauna over time.

- **A** Platypuses have become extinct in all states except Tasmania.
- **B** Kangaroos have become restricted to desert areas.
- **C** Eucalypts have become more widespread.
- **D** Rainforest species have become more widespread.

20 Which of the following statements most correctly describes how antibiotic resistance has developed in bacteria?

- **A** Colonies of antibiotic-resistant bacteria have developed as a result of the bacteria undergoing mutations in response to the antibiotics.
- **B** Some bacteria have a pre-existing allele that allows them to break down antibiotics. These bacteria increase in number in an environment containing antibiotics.
- **C** Bacteria that have undergone mutations in response to antibiotics pass on that resistance to other bacteria by horizontal transfer. These bacteria then increase in number.
- **D** Humans create antibiotic resistance in bacteria by not taking all of the antibiotics in a course that has been prescribed by a doctor.

Short answer

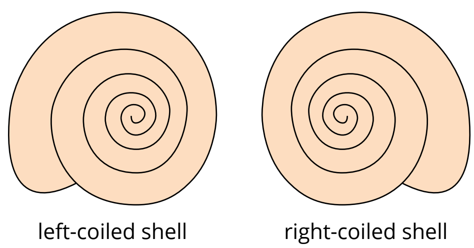
21 Australia is one of the world's most biodiverse nations. More than 80% of Australia's 2 million species of plants and animals are not found anywhere else in the world, making Australia a potentially rich area for finding new biological resources (bioprospecting) and for developing models based on biomimicry. You may need to access the internet to answer the following questions.

- **a** Distinguish between bioprospecting and biomimicry.
- **b** Give an example of biomimicry.
- **c** Suggest how conservation of species for bioprospecting can provide avenues for innovation in biomimicry.

22 Sometimes two separate species can interbreed to create a hybrid species. For example, a zebra and a horse can interbreed to produce a zorse. Zebras have 46 chromosomes and horses have 64 chromosomes, organised in matching pairs, for each body cell. This is known as the diploid number. A sex cell (gamete) has half the number of chromosomes; one of each chromosome pair, known as the haploid number.

- **a** Define the term 'species'.
- **b** How many chromosomes (haploid number) would you find in the gamete (sperm or egg) of a:
  - **i** zebra?
  - **ii** horse?
- **c** What is the diploid number of a zorse?
- **d** Would you predict that the zorse could become a new species? Explain your answer.

23 *Lymnaea* is a genus of mollusc with snail-like shells. Members of *Lymnaea* have shells that coil either left or right. In most individuals, development of this trait is purely genetic, with offspring showing a phenotype that is identical to the maternal phenotype. Occasionally, and seemingly at random, an environmental factor influences the outcome and an individual with a genetically right-coiling shell grows a shell that coils left and vice versa.



- **a** As a result of physical incompatibility, individuals with shells that coil in the opposite direction are unable to mate.
  - **i** If the environmental effect were to disappear, the two populations would find mating very difficult. What name is given to this sort of isolation?
  - **ii** Without the occasional environmental effect on shell growth this incompatibility could lead to speciation of the two groups. Explain how this could occur.
- **b** Why is speciation unlikely as long as the environmental effect continues to create individuals that are genetically of one form but phenotypically of the other form?

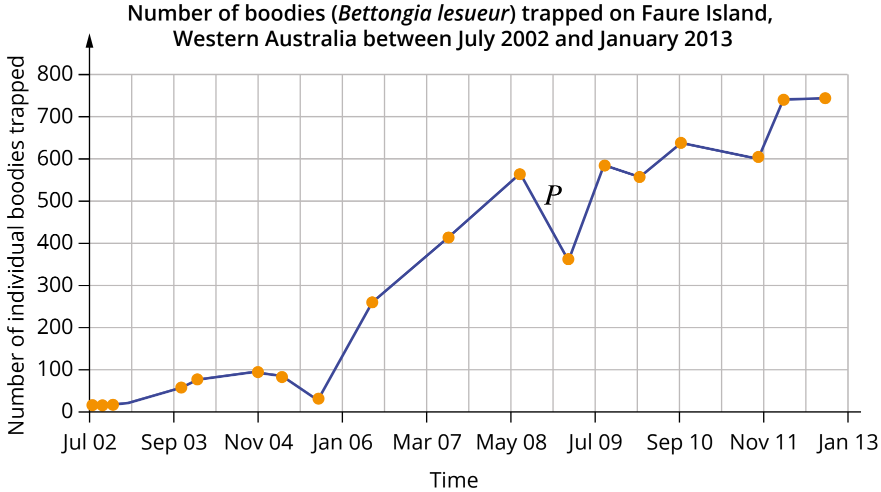
24 Boodies (*Bettongia lesueur*) are a species of rat-kangaroo that were reintroduced into an animal sanctuary on Faure Island, Western Australia. The sanctuary is free of introduced species. The boodie population has been monitored using a trap-and-release method. The graph below shows the changes in the population from July 2002 to January 2013.

a Explain why there is a slow increase in population on the island from July 2002 to November 2004.

b Propose an explanation for the fall in the boodie population at point P.

c Do you think that the population has reached carrying capacity? Explain your answer.

Number of boodies (*Bettongia lesueur*) trapped on Faure Island, Western Australia between July 2002 and January 2013

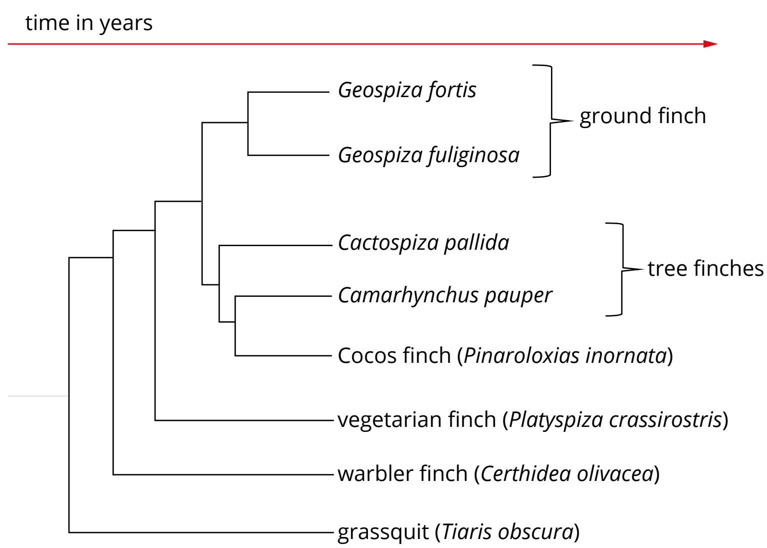


25 The following diagram shows a phylogenetic tree of Darwin's finches based on evidence from mitochondrial DNA.

a The finches *Geospiza fortis* and *Geospiza fuliginosa* belong to the same genus. Why might these organisms be classified as the same genus but different species?

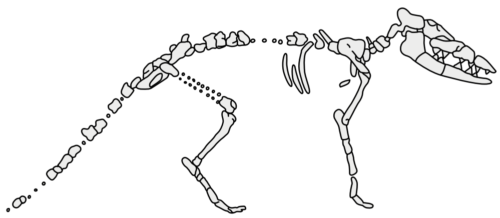
b Explain why scientists do not use common names such as 'tree finches' when they are communicating with other scientists.

c Based on the phylogenetic tree, which finch would you expect to be the most different from the other finches?

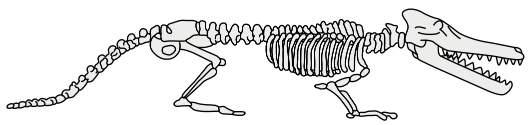


26 The fossil record has been an important source of evidence to support the theory of evolution.

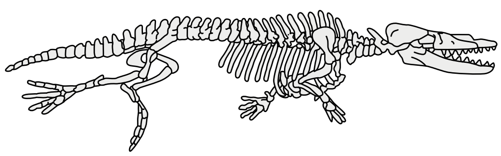
Shown below is a series of fossil skeletons showing the evolution of modern whales.



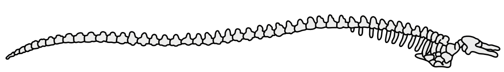
Pakicetus, about 50 mya 50 cm



Ambulocetus, about 49 mya 50 cm



Rhodocetus, about 47 mya 50 cm

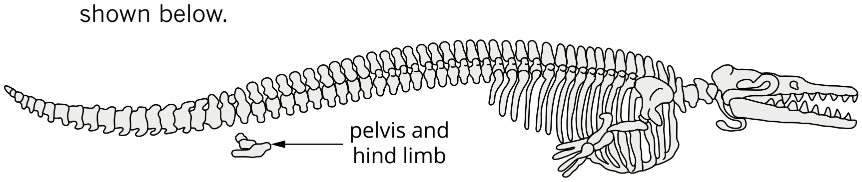


Basilosaurus, about 38 mya 50 cm

a Explain how this group of fossils provides evidence for evolution.

b Describe how the age of the *Ambulocetus* fossil was determined.

c *Dorudon* was another whale ancestor. Its skeleton is shown below.



Dorudon

Dorudon was a contemporary (more recent relative) of one of the above organisms. Which of the fossil series is this most likely to be? Provide reasoning to support your answer.

27 Summarise how an accumulation of microevolutionary changes has influenced the evolution of the platypus. In your response ensure the following areas of evidence are described: their size, their distribution and their morphological changes.

28 Describe the following techniques used to date fossils and rock. Outline the applications or limitations of each.

a relative dating

b indicator fossils

c absolute dating using radiocarbon dating

29 The half-life of carbon-14 is 5730 years.

a If a fossil sample originally included 1.0 g of carbon-14, how much would be left after 5730 years?

b How much would be left after 11 460 years?

c How many years would it take for the amount to be 0.125 g?

30 Wheat (*Triticum* sp.) is one of the world's major food crops. A disease that causes severe crop losses is wheat leaf rust. This disease is caused by three species of fungus, all of which belong to the genus *Puccinia*. Leaf rust fungus is found in all major wheat-growing areas, including Australia. Leaf rust can cause crop losses of up to 20% when infection occurs. Cost of *Puccinia* infections to farmers in Australia is about $127 million annually. This has resulted in significant research into methods of fighting the disease.

Resistant strains of wheat have been identified and selective breeding has been used to enhance the offspring of these strains. One such strain, called Norm, has been shown to have strong resistance to leaf rust fungus.

- **a** Around 46 different genes have been shown to be associated with resistance to the leaf rust fungus. Scientists have selectively bred varieties of wheat to increase the frequency of the alleles conferring the most resistance in wheat plants. Selective breeding for particular traits can have unexpected effects on the phenotypes of the organisms that have been subject to this process. Explain why.
- **b** The identification of Norm as highly resistant to leaf rust means that many farmers are deciding to plant this variety of wheat. Some scientists consider the exclusive use of one strain to be a very dangerous practice that could lead to worldwide famine. Do you agree with the scientists? Explain why or why not.
- **c** **i** Are these resistant populations of wheat likely to maintain their resistance to leaf rust fungus over the long term? Explain.
  - **ii** What kind of evolution is being demonstrated by the wheat and the leaf rust fungus?

Extended response

31 The introduction of cane toads (*Rhinella marina*) to Australia in the 1930s is one of the most well-known examples of an exotic animal release gone wrong. Originally imported from Hawaii and released in Queensland as a biological control for beetle pests of sugar cane, the cane toad is now a well-established pest itself. Read the following information about cane toads to answer the questions.

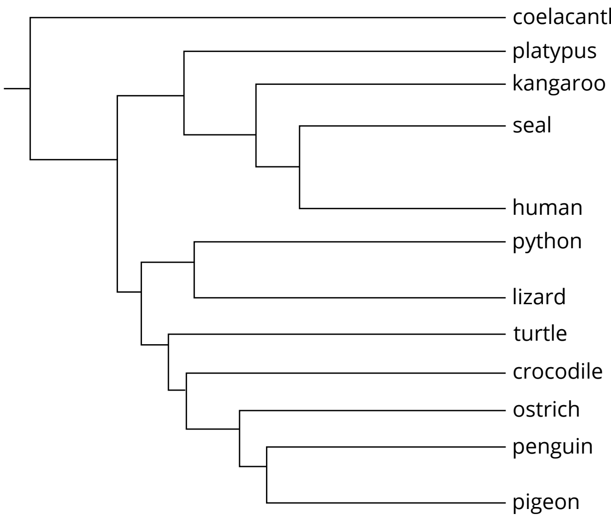
- Cane toads produce toxins at all stages of their life cycle but their toxicity varies at each stage. Eggs are highly toxic, tadpoles produce lower levels of toxin, toxicity is reduced further during metamorphosis from tadpole to adult, and there is a rapid increase in toxin production in adults. Adult cane toads' toxins can kill many animals that eat them.
- Adult female cane toads can lay up to 30 000 eggs in each clutch twice a year. Native frog species usually lay much smaller clutches.
- Cane toads are long-lived for a small animal, with a lifespan of 10–15 years in the wild.
- Older cane toad tadpoles produce pheromones that reduce the growth and survival of the younger cane toad tadpoles around them. This is an example of intraspecific competition.
- Cane toads can survive in a broad range of environmental conditions such as droughts and temperatures ranging from 5–40°C.
- Cane toads do not have a defined home range. Most cane toads will travel over 200 m in a single night. Toads at the migration front have evolved longer legs and larger bodies, enabling them to move faster.
- Cane toads are not able to prevent drying out via their skin (unlike many frog species, which have a waxy coating on their skin to prevent water loss). To conserve water, adults use retreat sites (e.g. under leaf litter) during the day and change their location seasonally. During the dry season, they often use burrows.
- Cane toads are generalists. They are opportunistic feeders and will eat any animal that is small enough for them to swallow. Their diet mainly consists of beetles, ants and termites but they have also been observed eating other toads, scorpions and spiders.
- Chemical sprays can be used to anaesthetise and kill cane toads.
- Some Australian native predators and domestic animals, such as cats and dogs, are highly vulnerable to cane toad poisoning because they have not evolved in the presence of cane toads. Large predators such as snakes, lizards, freshwater crocodiles and quolls are most at risk from cane toad poisoning because they can consume whole adult toads. Some native species are not susceptible to the cane toads' toxin and others (e.g. the red-bellied black snake) have evolved behavioural and physiological adaptations in response to cane toad poisoning, such as avoidance of the toads or tolerance of the toxin.

a Analyse the cane toad information and present a summary of:
- **i** biotic and abiotic factors that act as selection pressures on cane toads
- **ii** characteristics that are likely to increase their distribution and abundance

iii characteristics that are likely to decrease their distribution and abundance.

b Use the theory of evolution by natural selection to explain how some native species may have evolved to avoid death by cane toad toxin.

32 Birds and mammals share a common ancestor. The ancestor of these two classes was a terrestrial vertebrate. Today some species in both groups spend large amounts of time in an aquatic environment. Two such species are penguins and seals. The hypothesised evolution of both of these groups is shown in the phylogenetic tree below.



The last common ancestor of penguins and seals was a vertebrate that lived some time between 305 and 340 million years ago. Evidence suggests that, like modern reptiles, this organism was ectothermic.

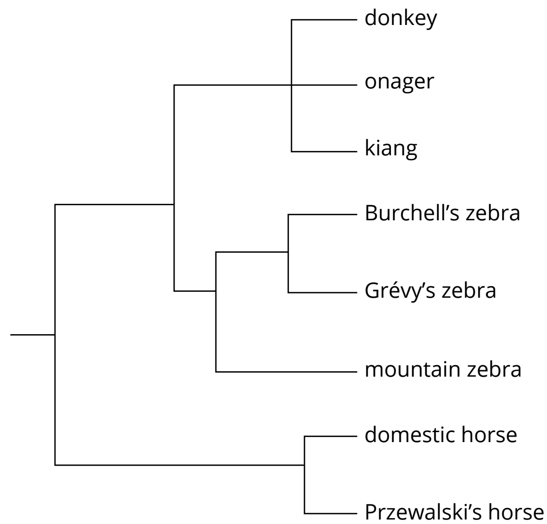
a Penguins and seals are both endothermic. Explain what kind of evolution has resulted in the two groups having this characteristic.

b Discuss why there is so much uncertainty about when the last common ancestor of penguins and seals lived.

c Seals and penguins both have forelimbs modified as flippers. These flippers can be considered both homologous and analogous. Explain how both can be correct.

33 The genus *Equus* includes several species, both extinct and extant (still living). The extant species includes two species of horse: Przewalski's horse (*Equus przewalskii*) and the domestic horse (*Equus caballus*). Przewalski's horse is listed as Endangered. In 1945, 13 individuals were bred in captivity. All current members of the species are descendants of nine members of this captive population. The last wild member of *Equus przewalskii* was seen in 1965, shortly after which it was determined that it was Extinct in the wild. Since then, a conservation and breeding programme based on the original nine members of the captive population has been so successful that they were re-introduced into their natural habitat, the steppes of Mongolia. The wild population now numbers over 400 and the captive population is more than 1500.

The phylogenetic tree for the genus *Equus* is shown below.



a The population of Przewalski's horse from which the current population descended was quite small in number. Does this represent a genetic bottleneck or a founder population? Justify your answer.

b Despite the considerable increase in the numbers of Przewalski's horse, it is still considered to be Endangered. Explain why this is the case.

c The nearest living relative of Przewalski's horse is the domestic horse. Przewalski's horses have 66 chromosomes and domestic horses have 64. Despite this difference, matings between domestic horses and Przewalski's horses produce fertile offspring. You may need to access the internet to answer the following questions.

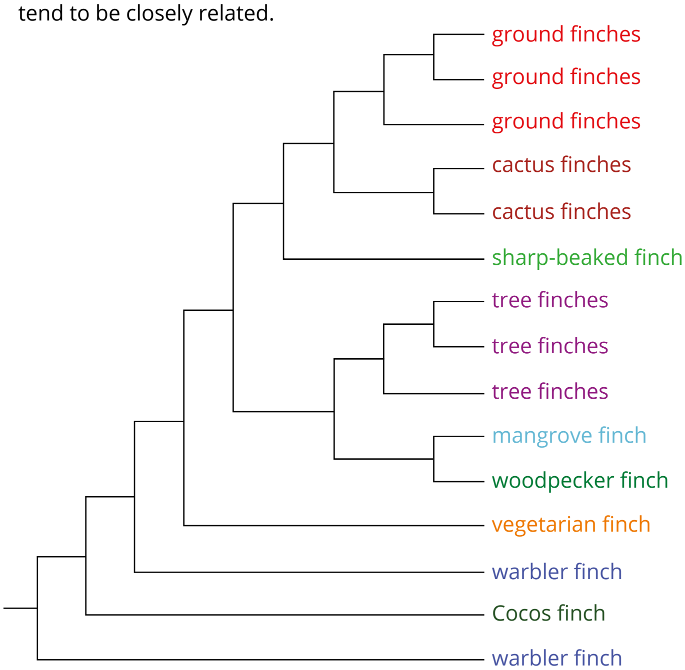
- **i** How might the change in chromosome numbers have come about?
- **ii** Przewalski's horse and the modern domestic horse are very closely related. The relationship is so close that some taxonomists classify them as subspecies of the same species: *Equus ferus*. What is a subspecies?
- **iii** Why might there be so much argument about whether Przewalski's horse and the domestic horse are separate species or subspecies of *Equus ferus*?

34 While on his famous trip on the HMS *Beagle*, Darwin observed finches on the Galápagos Islands. The islands contain 13 different species of these birds. On the Cocos Islands there is a 14th species of finch that is related to the Galápagos finches. The Galápagos finches are hypothesised to be most closely related to the tanager finches of Central and South America.

The map below shows the relationship between the islands and the mainland of South America.

The hypothesised relationships between the various finches is shown in the phylogenetic tree.

Genetic sequences show that finches with similar feeding styles tend to be closely related.



a DNA studies were used to establish that the Cocos Island finches are closely related to the Galápagos finches. What is the name of the technique that uses DNA to identify relationships between species?

b According to the phylogenetic tree shown, which of the Galápagos groups is most closely related to the Cocos Island finches?

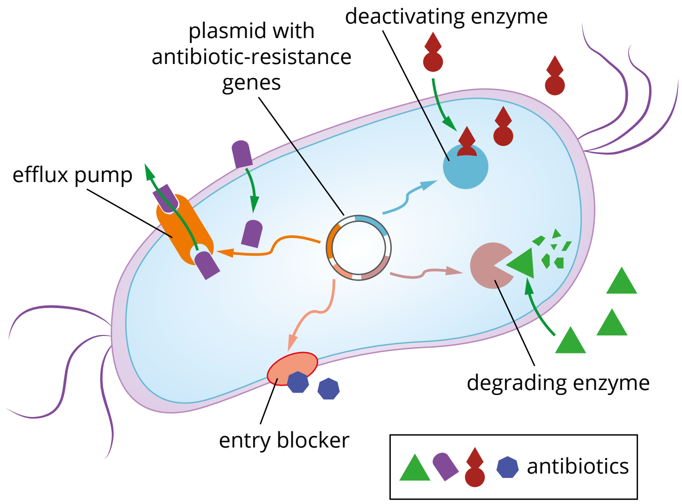
c The finches of the Galápagos Islands show considerable genetic variation. What does this suggest about the size of the founder population?

d It is thought that the first finches arrived on the Galápagos about 2 million years ago. Since that time the environment has changed considerably. There has been volcanic activity, which added 14 islands to the chain. There have also been changes in sea level, isolating some islands, and the climate has changed from lush and tropical to cool and dry.

How might the changes in the Galápagos Islands have resulted in speciation of the original population of finches to arrive there? Use examples from the phylogenetic tree to support your answer.

35 Bacteria that are exposed to antibiotics can develop a resistance to them. The development of drug resistance has become a significant problem, limiting the usefulness of many of these drugs. For example, there was a time when penicillin killed more than 97% of all *Staphylococcus aureus* (also known as golden staph) bacteria, which can cause blood infection (sepsis). Now in Australia 80–90% of these bacteria are resistant to penicillin and about 20% are resistant to a higher-level antibiotic, methicillin.

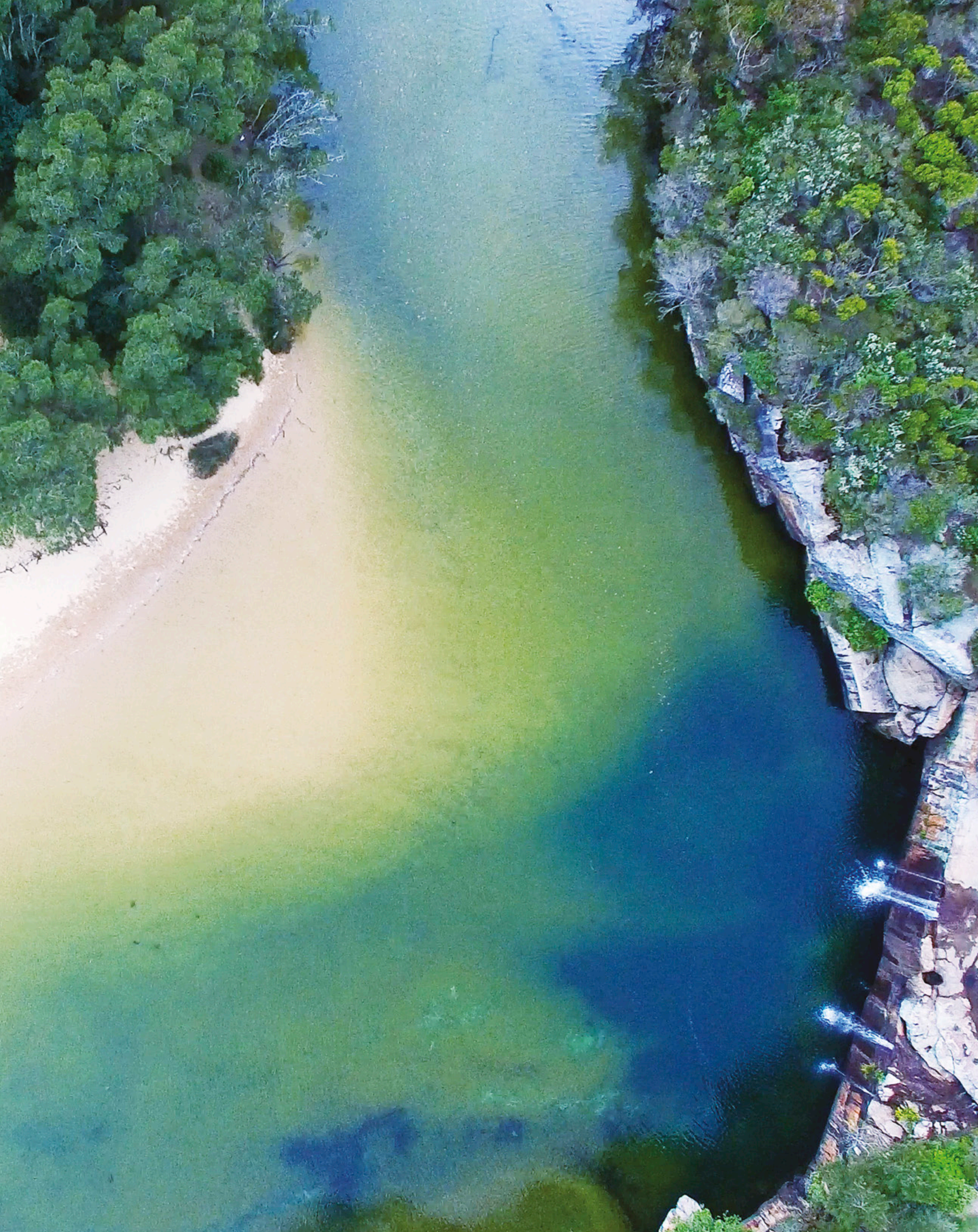
The diagram shows some mechanisms of bacterial resistance. Many bacteria have additional small rings of double-stranded DNA called plasmids. Use this information to answer the questions below.



a List the number of ways shown in the diagram for bacteria to resist antibiotics.

b Given that bacteria do not reproduce sexually and mix genetic information from two parents, explain how genetic variation arises in the bacterial population, leading to evolutionary change.

c MRSA is the code for methicillin-resistant *S. aureus*. Assess the future risk of MRSA to humans.



MODULE 4

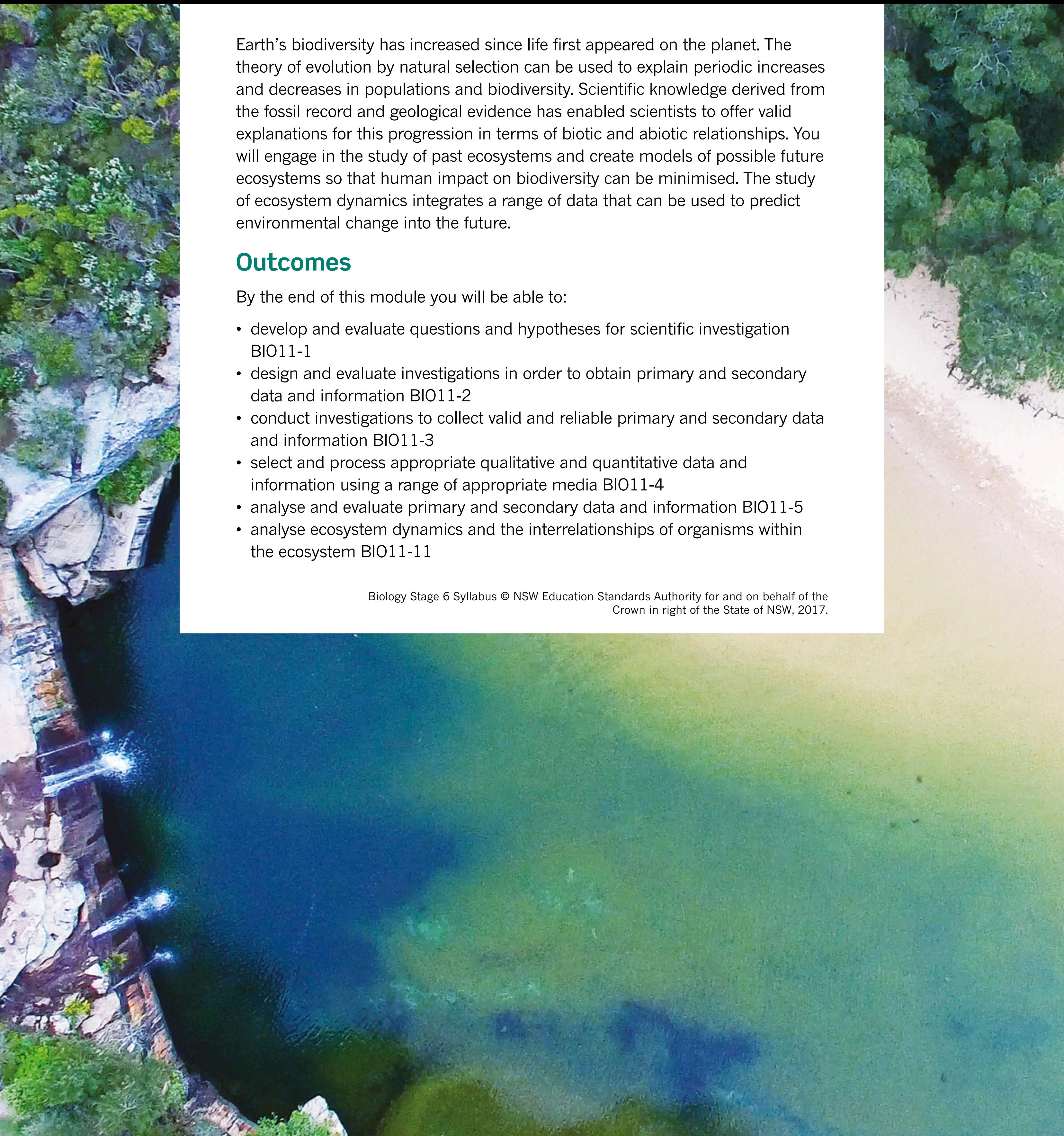
Ecosystem dynamics

Earth's biodiversity has increased since life first appeared on the planet. The theory of evolution by natural selection can be used to explain periodic increases and decreases in populations and biodiversity. Scientific knowledge derived from the fossil record and geological evidence has enabled scientists to offer valid explanations for this progression in terms of biotic and abiotic relationships. You will engage in the study of past ecosystems and create models of possible future ecosystems so that human impact on biodiversity can be minimised. The study of ecosystem dynamics integrates a range of data that can be used to predict environmental change into the future.

Outcomes

By the end of this module you will be able to:

- develop and evaluate questions and hypotheses for scientific investigation BIO11-1
- design and evaluate investigations in order to obtain primary and secondary data and information BIO11-2
- conduct investigations to collect valid and reliable primary and secondary data and information BIO11-3
- select and process appropriate qualitative and quantitative data and information using a range of appropriate media BIO11-4
- analyse and evaluate primary and secondary data and information BIO11-5
- analyse ecosystem dynamics and the interrelationships of organisms within the ecosystem BIO11-11



CHAPTER 11

Population dynamics

This chapter will explore the relationships between biotic and abiotic factors in an ecosystem, including the interactions between species and the ecological niches they occupy. You will examine the techniques biologists use to measure and understand population dynamics and look at how this enables scientists to predict the consequences of biotic and abiotic interactions for populations. Population dynamics and ecosystem functioning will also be studied with reference to recent extinction events.

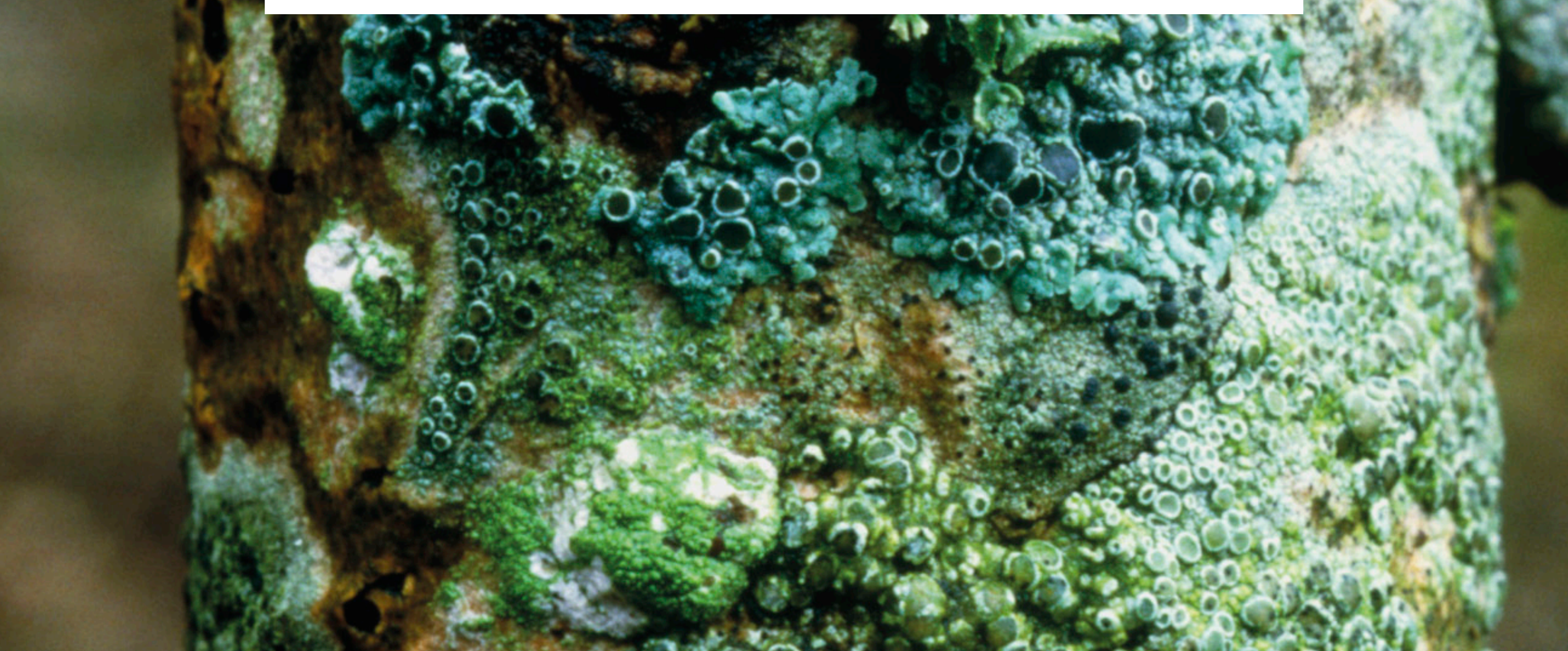
Content

INQUIRY QUESTION

What effect can one species have on the other species in a community?

By the end of this chapter you will be able to:

- investigate and determine relationships between biotic and abiotic factors in an ecosystem, including (ACSBL019): S CCT ICT PSC
  - the impact of abiotic factors (ACSBL021, ACSBL022, ACSBL025)
  - the impact of biotic factors, including predation, competition and symbiotic relationships (ACSBL024)
  - the ecological niches occupied by species (ACSBL023)
  - predicting consequences for populations in ecosystems due to predation, competition, symbiosis and disease (ACSBL019, ACSBL020) S
  - measuring populations of organisms using sampling techniques (ACSBL003, ACSBL015) ICT N
- explain a recent extinction event (ACSBL024) S L



11.1 Relationships between biotic and abiotic factors in an ecosystem

DS 4.1 WS 4.1

BIOLOGY INQUIRY CCT ICT L

Ecological interactions

What effect can one species have on the other species in a community?

COLLECT THIS…

- sheet of cardboard
- coloured pencils and pens
- tablet or computer to access the internet

DO THIS…

1 Working in groups of two or three students, choose a plant or animal species that you would like to research (some examples are listed below):
   - red kangaroo (*Macropus rufus*)
   - common ringtail possum (*Pseudocheirus peregrinus*)
   - yellow mangrove (*Ceriops tagal*)
   - snow leopard (*Panthera uncia*)
   - Venus flytrap (*Dionaea muscipula*)
   - red slender loris (*Loris tardigradus*)
   - red river gum (*Eucalyptus camaldulensis*)
   - grey nurse shark (*Carcharias taurus*)
   - Atlantic salmon (*Salmo salar*)
   - Australian green tree frog (*Litoria caerulea*)
   - eastern brown snake (*Pseudonaja textilis*)
   - tawny frogmouth (*Podargus strigoides*)

2 Take 10 minutes to research how your selected species interacts with other species in its environment; for example:
   - Type of interaction
     - Does it interact with other species of plants/animals in food chains/webs?
     - Does it interact with other species of plants/animals when looking for food/water/shelter?
   - The species it interacts with
     - Species name
     - How many other species does this species regularly interact with?
   - The result of the interaction
     - Does one species benefit and the other not?
     - Does one species move to another community?

3 Create a diagram representing the interactions between your chosen species and the other species in its community.

RECORD THIS…

Describe the ways in which species interact with each other in an environment.

Present your diagram representing the species interactions to the class.

REFLECT ON THIS…

What effect can one species have on the other species in a community?
How might one species drive the evolution of another species?
How might one species cause the extinction of another species?

Communities are made up of different organisms grouped together at a given time and place. On a larger scale, these communities interact with other communities and their physical surroundings, and are classified as **ecosystems**. For example, Wollemi National Park in the Greater Blue Mountains World Heritage area, New South Wales (Figure 11.1.1) is a dynamic ecosystem with communities of flora and fauna such as grey box eucalypts and wombats interacting with their physical environment of sandstone gorges, canyons and river valleys.

This section explores the interactions between biotic and abiotic factors in an ecosystem including the ways in which organisms interact with their environment (e.g. physical barriers, migration across landscapes and the use of abiotic resources) and the ways in which organisms interact with one another (e.g. predation, competition and symbiotic relationships).

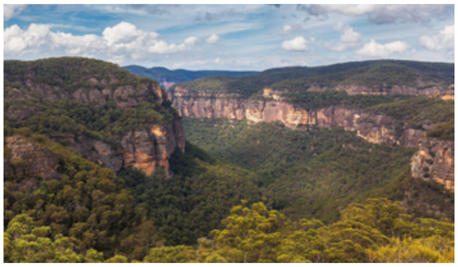


FIGURE 11.1.1 The dynamic ecosystem of Wollemi National Park in the Greater Blue Mountains region of New South Wales

ABIOTIC FACTORS SHAPE ECOSYSTEMS

Organisms affect, and are affected by, their physical surroundings. For example, earthworms live in soil, where they bury and consume dead plant material. This helps to recycle nutrients and aerate the soil. Like all animals and plants, earthworms take in oxygen, water and nutrients and give out carbon dioxide and other wastes. Plants take in carbon dioxide and produce oxygen during photosynthesis. Without the first photosynthetic organisms that evolved billions of years ago, Earth's atmosphere would have lacked oxygen and the biosphere would be very different today.

The interdependency, or strong connection, between **biotic** and **abiotic** factors is key to ecosystem functioning. Abiotic factors determine where organisms can and cannot live (their **distribution**) and if an organism reproduces, thrives or dies. Biologists can use information about abiotic factors to predict an organism's growth, **abundance** and distribution and understand how changes in abiotic factors might affect **species**.

The changing Earth

The conditions on Earth have always determined the variety of living organisms that can exist. Earth's atmosphere has changed remarkably over time. The early Earth, which formed 4.6 billion years ago, was volcanically very active and the atmosphere was very different from that of today. **Climates** (long-term weather conditions) changed over time, and there have been multiple ice ages and hot, dry periods. Ice ages, or glacial episodes, affected Earth's climates by changing sea levels and affecting air and water circulation, leading to species migration, shifts in vegetation zones and species **extinction**. These historical changes have influenced and shaped the ecosystems we see on Earth today.

The movement of the large **tectonic plates** that make up Earth's crust has also shaped environmental conditions. As the positions of land masses and oceans has changed throughout Earth's history, so too have ocean circulation patterns, climatic conditions and many abiotic and biotic factors. Oceans are also barriers to the migration of terrestrial (land) species and influence the distribution of marine organisms. Ocean ecosystems are especially affected by plate tectonics as **mid-ocean ridges** (underwater mountain ranges formed when two tectonic plates meet, causing the ocean floor to lift) are responsible for the spread and depth of oceans, as well as the development of ocean 'climates'.

The movement of tectonic plates continues to shape modern ecosystems. For example, tectonic activity near Japan led to the eruption of a new volcano and emergence of a new land mass known as Nishinoshima in 2013 (Figure 11.1.2). The land mass now covers approximately 2.46 km^2 and although it is mostly bare rock derived from cooling lava, deposits of faeces from birds flying over Nishinoshima are leading to the development of nutrient-rich soil. Recent studies on the island in 2016 identified the presence of primitive plants and insects.

FIGURE 11.1.2 The emergence of a new land mass, Nishinoshima, creates a new ecosystem as a result of plate tectonics.

BIOLOGY IN ACTION S

Crater of the lost

In 2009 an expedition discovered that the extinct Mount Bosavi volcano, located in the Southern Highlands of Papua New Guinea, had become home to a uniquely isolated ecosystem (Figure 11.1.4).

FIGURE 11.1.4 The extinct Mount Bosavi volcano is a unique and isolated ecosystem with species found nowhere else in the world.

The volcano has not erupted for at least 200 000 years, allowing a unique tropical rainforest ecosystem to evolve in its 4 km wide, 1 km deep crater. The tropical rainforest has an extremely hot, humid microclimate. Researchers have found more than 40 unique species in the Bosavi rainforest. These species have never been documented and are found nowhere else in the world. Species include the Bosavi woolly rat, Bosavi silky cuscus mammal and the king bird of paradise (Figure 11.1.5). Scientists reached the ecosystem by helicopter followed by a four-day trek, with specialist tree-climbers and local people.

FIGURE 11.1.5 The king bird of paradise (*Cicinnurus regius*), one of the species discovered in Mount Bosavi's crater ecosystem

BIOFILE S

Cave ecosystems

An ecosystem strongly shaped by abiotic factors is the Son Doong Cave in Vietnam (Figure 11.1.3). Discovered in 1961, and only explored in 2009, the cave is the largest known in the world measuring at a whopping 200 m high, 150 m wide and over 5 km long. The cave formed on the edge of a fault zone and is so large it has its own forest, localised weather system and river. Where sections of the cave ceiling have collapsed, sunlight has allowed the growth of lush tropical vegetation. Scientists are still discovering new species in the cave such as monkeys, amphibians and insects, and even albino organisms that have adapted to the dark areas of the cave.

FIGURE 11.1.3 Son Doong Cave in Vietnam formed on the edge of a fault zone and is the largest known cave in the world. It contains a unique ecosystem, including its own weather conditions, forest and river.

Climate zones

Differences in climate have created many varied terrestrial and aquatic ecosystems, from the frozen soil of the tundra landscape, home to polar bears and caribou, to the tropical waters of the coral reef with its shallow pools, clownfish and turtle species.

- **Climate zones**, or belts, are regions of distinct climates occurring in an east-to-west direction across Earth (Figure 11.1.6). Solar radiation determines many aspects of Earth's climatic zones; ecosystems at latitudes close to the equator are exposed to more sunlight than ecosystems towards the North and South Poles. Solar radiation also determines the seasons and other factors such as rainfall, which influence the characteristics of climates. There are three main climate zones: tropical, temperate and polar (Figure 11.1.6). A fourth zone, subtropical, is sometimes used to describe the region between the tropical and temperate zones.
- **Polar zones** are the coldest regions on Earth, with the least solar radiation. Temperatures are often below freezing throughout the year and ecosystems in the polar zone have low **biodiversity** (variety of species). The polar zone is towards the North and South Poles at the highest latitudes on Earth (blue regions in Figure 11.1.6).
- **Temperate zones** have moderate temperatures and rainfall, with seasonal variation throughout the year. The temperate regions on Earth are located between the polar and tropical zones (green regions in Figure 11.1.6). Many parts of the temperate zone are rich in biodiversity.
- **Tropical zones** are the warmest and wettest regions on Earth. The tropics experience the most solar radiation because they are located close to the equator, where radiation from the Sun is almost perpendicular to Earth throughout the year (red/orange regions in Figure 11.1.6). The high rainfall and high temperatures in the tropics support ecosystems with high biodiversity. Tropical rainforests and most coral reef ecosystems are found in the tropical zone.

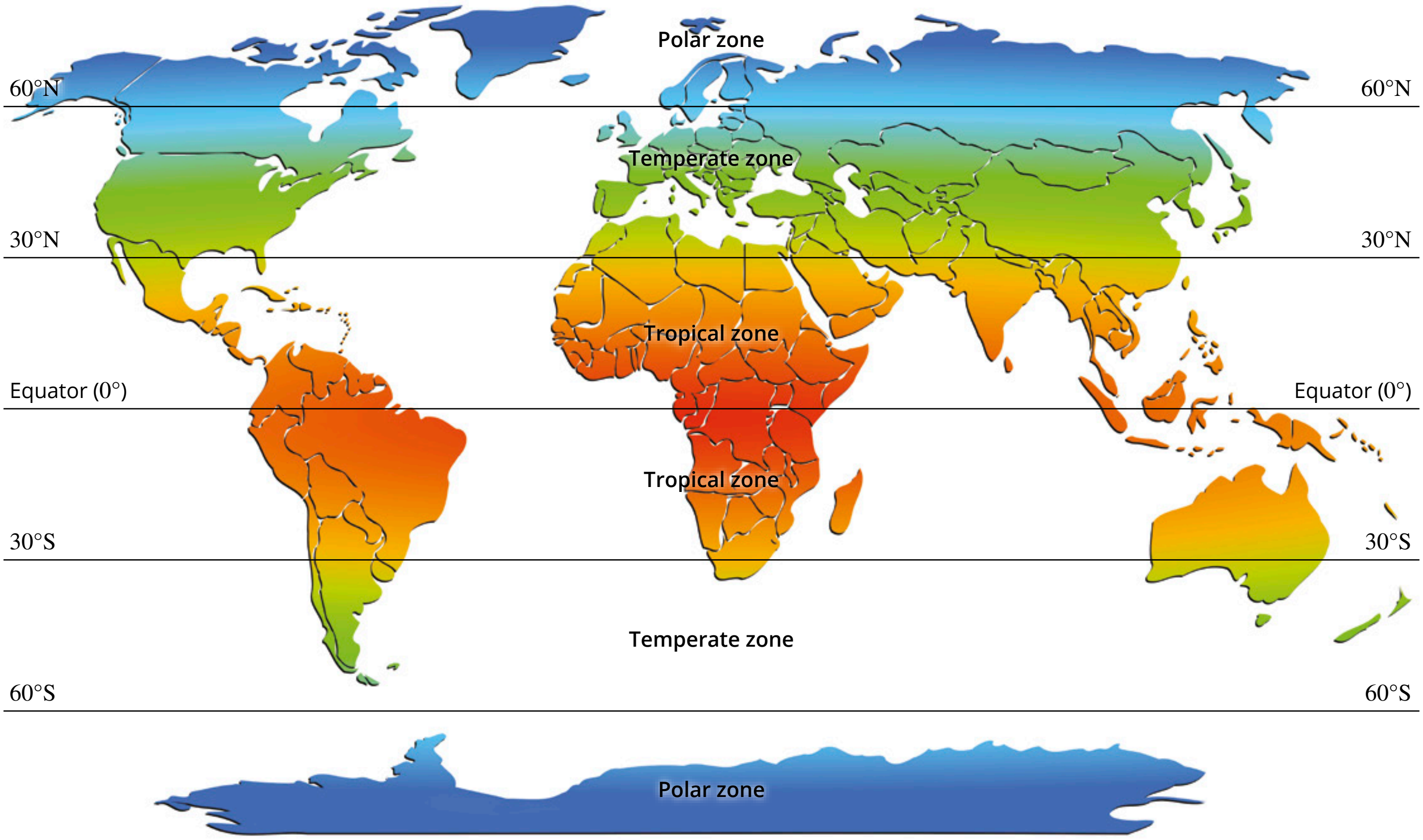


FIGURE 11.1.6 Main climatic zones according to latitude

Climate plays an important role in ecosystem functioning, not only determining the organisms found in that ecosystem, but also the behaviour and interactions of organisms. Climate affects many life cycle events such as the migration of species, germination and breeding. For example, humpback whales (*Megaptera novaeangliae*) spend the summer months feeding in the cold waters of Antarctica. By late autumn, the whales commence their annual migration along the east coast of Australia to the warmer tropical waters of the Pacific Ocean to breed and give birth (Figure 11.1.7).

FIGURE 11.1.7 The annual migration of the humpback whale (*Megaptera novaeangliae*) is driven by climate factors and affects its feeding and breeding behaviour.

Changing climates

Every ecosystem has a '**threshold**'—a point past which the ecosystem changes irreversibly. Human-induced climate change is one significant contributor to ecosystems passing this threshold. Climate change affects all aspects of ecosystem functioning, from life cycle events such as flowers blossoming, to changes in species' distributions and food webs.

For example, multiple species of whales are being affected by climate change, with rising ocean temperatures causing the populations to migrate earlier and travel further. With increasing ocean acidification, birth rates are dropping and breeding grounds are changing. Krill are an important food source for many species of whales, and responsible for increasing their body fat ahead of migration. Krill populations are drastically declining due to rising ocean temperatures.

The impact of changing climates on ecosystems will be discussed further in Chapter 13.

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Biogeography

FIGURE 11.1.8 The island of Madagascar, located off Africa's coastline, is home to many endemic species.

Biogeography is the study of species' distributions to understand their evolutionary past and the abiotic and biotic factors that might determine species' abundance and distribution now and in the future. For example, the island of Madagascar (Figure 11.1.8) has been studied with interest by biogeographers for a long time. Madagascar is located in the Indian Ocean off Africa's south-east coast and is home to many **endemic** species (species that are found nowhere else on Earth). Biogeographers have investigated why there are so many unique species on Madagascar and have discovered that large-scale abiotic factors such as geology, geography and climate have all influenced the distribution and abundance of species.

Madagascar was landlocked in the supercontinent Gondwana 170 million years ago, before breaking apart and remaining isolated for the last 88 million years. It is believed that some species from the supercontinent remained on Madagascar, while others arrived on the island after Madagascar had broken away. After becoming isolated, the species on Madagascar evolved unique adaptations, different to those species on mainland Africa. Madagascar's species had many different abiotic factors to adapt to, with ecosystems on the island including mountain ranges, rainforests (Figure 11.1.9a), deserts, coral reefs and mangroves. As a result, Madagascar is home to species including baobab trees (Figure 11.1.9b), lemurs (Figure 11.1.9c), tortoises, chameleons and comet moths (Figure 11.1.9d). Madagascar is very high in biodiversity, that is, the variety of organisms that live in a particular habitat.

FIGURE 11.1.9 Madagascar has many unique, species-rich ecosystems, such as (a) tropical rainforests and (b) the baobab tree fields. These ecosystems are home to many species that are found nowhere else in the world, including (c) the Critically Endangered black and white ruffed lemur (*Varecia variegata*) and (d) the comet moth also known as the Madagascan moon moth (*Argema mittrei*), one of the world's largest silk moths.

Biodiversity

High biodiversity is closely linked to latitude and climate. The abundance of species per unit area (**species richness**) increases from the poles to the equator, with the highest biodiversity at the tropics near the equator. Over 50% of the species on Earth live in the tropics. Abiotic factors in tropical regions strongly contribute to this high species diversity, including a more stable climate, warm temperatures, high levels of rainfall and a higher level of **primary productivity** (plant growth), which supports more consumers (animals, fungi and bacteria).

BIOLOGY IN ACTION S

Biodiversity hotspots

Biodiversity hotspots are ecosystems with a high diversity of endemic species. They are also ecosystems that are under threat from human impacts and where biodiversity conservation must be prioritised.

The Brigalow Belt bioregion in New South Wales and Queensland is one of Australia's 15 biodiversity hotspots. The inland plains of the Brigalow Belt (Figure 11.1.10) are named after the Brigalow acacia (*Acacia harpophylla*) and are home to eucalypt woodlands and many endangered species including the semi-evergreen vine thickets and the northern hairy-nosed wombat (Figure 11.1.11), bridled nail-tail wallaby and jewel butterfly. Threats to this ecosystem include agriculture and grazing, which continue to degrade the native vegetation and encourage invasion by weeds, as well as introduced species such as cats and foxes (Figure 11.1.12). The Brigalow Belt requires targeted action to manage these threats and conserve its unique ecosystems.

FIGURE 11.1.10 The Brigalow Belt bioregion in New South Wales and Queensland is considered a biodiversity hotspot because of its high level of biodiversity and the need for targeted conservation measures to protect its ecosystems.

FIGURE 11.1.11 The northern hairy-nosed wombat (*Lasiorhinus krefftii*) is an Endangered species of the Brigalow Belt.

FIGURE 11.1.12 Foxes prey on many Endangered species in the Brigalow Belt bioregion, including marsupials such as wallabies.

BIOTIC FACTORS SHAPE ECOSYSTEMS

WS 4.2

The manner in which biotic factors interact also affect the growth, abundance and distribution of communities in an ecosystem. In an ecosystem, the organisms interact and depend upon one another for survival. They influence one another by being part of each other's environment. Interactions between organisms can be harmful, neutral or beneficial.

INTERACTIONS BETWEEN SPECIES

Interactions between species are called **interspecific** interactions and interactions within species are called **intraspecific** interactions. These interactions are usually classified according to how the interaction affects the survival and reproduction of the organisms involved.

Some interactions involve organisms acting in opposition to one another (**competition** and **predation**) and some interactions involve organisms working together (**symbiosis**). Interactions between species can also be classified as feeding and non-feeding interactions.

Competition

The presence of other organisms may limit the distribution of some species through interspecific competition. Interspecific competition is a struggle between organisms of different species for the same supply of food, water, space, nest sites or any other environmental resource that is in limited supply. Intraspecific competition is competition between individuals of the same species.

Because they use similar resources, green plants mainly compete with other green plants, **herbivores** with other herbivores, and **carnivores** with other carnivores. Competition can lead to one species being forced out of a habitat by its competitor. The species that was outcompeted usually continues to survive in adjacent parts of the habitat.

For example, populations of two species of protists, *Paramecium aurelia* and *Paramecium caudatum*, will grow rapidly in separate but identical cultures, with both populations reaching a plateau when numbers get too high for the environment (Figure 11.1.13a, b). However, if these species are grown together, the population of *P. caudatum* grows initially, but then its population decreases to extinction (Figure 11.1.13c). In other words, *P. aurelia* **outcompetes** *P. caudatum*. *P. aurelia* continues to reproduce to reach a population density similar to when the species are cultured separately.

The kind of interaction seen in the *Paramecium* is called **competitive exclusion**—where one species is better at obtaining resources, excluding the other from the available resources and sometimes driving them to extinction. Other types of competition result in **resource partitioning**, where species change their behaviour and resource use, allowing both species to access resources in the same environment.

You will learn more about competition in ecosystems in Sections 11.2 and 11.3.

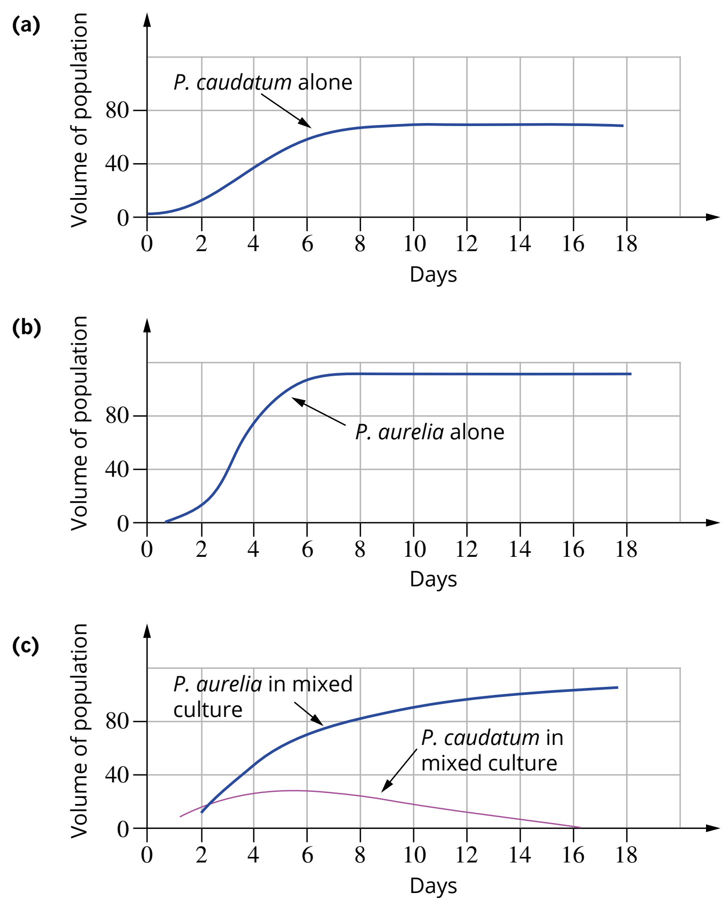

FIGURE 11.1.13 (a, b) When two species of *Paramecium* are cultured separately, their numbers increase until the environment limits their population growth. (c) When the two species are cultured together, the population growth of both species is slowed until eventually one species outcompetes the other.

Predation

Predation occurs when one animal species (the **predator**) kills and feeds on another animal (the **prey**). Predators are carnivores. Some predators hunt for their prey (Figure 11.1.14a) and others catch their prey in traps (Figure 11.1.14b). In both cases the predator benefits by eating and killing the prey, which is obviously harmed. The role of predation in ecosystems will be further discussed in 'Feeding interdependencies' on page 506 and Section 11.3.

FIGURE 11.1.14 (a) Lions, as well as tigers and other cats, are predators that hunt for their prey. (b) Spiders are predators that make webs to trap passing insects, which they then eat.

Symbiosis

Sometimes two quite different organisms live and function together in a close association for the benefit of at least one of them. Close, long-term relationships between different species are a type of symbiosis. Symbiosis can be beneficial for both organisms (**mutualism**), beneficial for one organism while not affecting the other (**commensalism**), beneficial for one organism and harmful for the other (**parasitism**), or harmful to one organism with no benefit to the other (**amensalism**) (Table 11.1.1). Each organism involved in the interaction is called a **symbiont**. Symbiotic relationships can be further classified as **obligate symbiosis** (necessary for survival) or **facultative symbiosis** (beneficial but not necessary for survival).

TABLE 11.1.1 Types of symbiosis

Type of symbiosis	Interaction	Example
mutualism	• benefits both organisms	• sea anemone and clown fish • The anemone provides shelter and protection for the clown fish and the clown fish provides nutrients for the anemone.
commensalism	• benefits one organism while not affecting the other	• shark and remora • Remora are small fish that feed on scraps of prey dropped by the shark. In this situation the remora benefit with no effect on the shark. As the remora also feed on parasites on the shark, this relationship can also be mutualistic because both species benefit.
parasitism	• benefits one organism while harming the other	• head lice and human • Head lice are parasitic insects that live on the human scalp and feed on blood. The lice benefit while the human is harmed.
amensalism	• harms one organism with no benefit to the other	• plant species and water birds • Plant species are often damaged and killed at water bird nesting sites due to the high levels of potassium, nitrogen and phosphorous in their droppings. This interaction harms the plants but does not affect the water birds.

BIOFILE CCT

Symbiosis in the sea

Cleaner fish and cleaner shrimps have a symbiotic relationship with their hosts. They eat dead skin and parasites on the surface of larger marine animals. Figure 11.1.15 shows a suckerfish attached to the shell of a sea turtle. The suckerfish eat food scraps from the feeding activity of the turtle, as well as parasites on the turtle's shell.

FIGURE 11.1.15 A suckerfish attached to the shell of a sea turtle in the Red Sea

Symbiosis is a relationship in which two quite different organisms live and function together in close association, to the benefit of at least one of them. Mutualism, commensalism and parasitism are all examples of symbiotic relationships.

Beneficial interactions

Mutualism

Mutualism is a symbiotic partnership that benefits both organisms. Some of the most common partners in mutualism are unicellular algae. The bright colours of corals, the green of some hydra and the brilliant blues of the mantles of giant clams are produced by algae living in the animal's tissues (Figure 11.1.16). The algae photosynthesise and produce glucose and oxygen, which are used by the animal. In turn, the animal produces carbon dioxide during respiration, which the algae need for photosynthesis. The algae also benefit by having safe shelter within the animal.

Sometimes organisms evolve adaptations that encourage symbiosis. For example, most flowering plants are adapted to attract pollinators. The plants have colourful flowers, nectar or fruit that attract animals such as bees and bats. The animals benefit by collecting food from the plant and the plant benefits as the animals pollinate their flowers or disperse their seeds. An example of this type of relationship is between the desert quandong or Australian native peach (*Santalum acuminatum*) and emus. The emu can digest the soft part of the desert quandong's fruit, but not the seed, which it passes out in its droppings. The droppings act like fertiliser and help the seed germinate and grow. The emu and quandong have a mutualistic relationship—the emus benefit from eating the fruit and the quandong benefits by having its seeds dispersed (Figure 11.1.17).

FIGURE 11.1.16 Giant clams and unicellular algae have a mutualistic relationship.

FIGURE 11.1.17 The fruits of the desert quandong or Australian native peach (*Santalum acuminatum*) are eaten by emus. Both species benefit from this mutualistic relationship—the emus benefit from eating the fruit and the quandong benefits by having its seeds dispersed.

Pollination is the transfer of pollen from an anther (in the male part of a flower) to a stigma (in the female part of a flower). Animals that transfer pollen are called pollinators and are in a mutualistic relationship with the plant.

BIOFILE CCT

Pollination adaptations

Many flowering plants have the anthers and stigmas on different flowers, so pollen needs to be transported from one flower to another. For plants such as grasses this happens by wind dispersal, but many plants rely on animals to do this for them. The wide variety of colours and scents in flowers is often due to the plant needing to attract a particular pollinator.

Because insects are more sensitive to blue and yellow wavelengths of light, flowers with insect pollinators are usually these colours. Insects also have a well-developed sense of smell, so insect-pollinated flowers usually emit a pungent scent. However, these are not necessarily pleasant. The carrion flower, a desert angiosperm, attracts flies by emitting the smell of rotting meat (Figure 11.1.18).

Birds such as hummingbirds are also efficient pollinators and are attracted to red and yellow flowers. Flowers pollinated by fruit-eating bats emit scents similar to that of ripe fruits.

Depending on how the species interact, pollination can be either obligate (necessary for survival) or facultative (not necessary for survival) mutualism.

FIGURE 11.1.18 The fly acts as pollinator for the carrion flower (*Stapelia gigantea*). The fly is attracted to the flower by the red and yellow petals and the smell of rotting meat.

BIOLOGY IN ACTION S

Bacteria and coral bleaching

Corals live in a symbiotic relationship with unicellular algae called zooxanthellae (Figure 11.1.19a). The photosynthetic algae provide food for the coral polyps and give corals their colour. The coral polyps produce a hard skeleton of calcium carbonate, which is a home for both organisms. Corals are bleached (become pale) and eventually die when they lose their zooxanthellae (Figure 11.1.19b). This can occur when sea temperatures rise, causing the coral polyps to become stressed and expel their algal partner. Increased coral bleaching has been connected with the rising sea temperatures associated with climate change.

It has been suggested that the increased bleaching of corals may be caused by a bacterial infection that occurs when the seawater temperature rises. In 2004 Eugene Rosenberg found a new species of bacteria, *Vibrio shiloi*, that is always associated with bleached and dying coral in the Mediterranean Sea. This species of bacteria is closely related to *Vibrio cholerae*, the bacteria that cause cholera.

Experiments found that coral did not bleach in water at 29°C, but did bleach at this temperature if *V. shiloi* was present. However, if the water temperature was only 16°C no bleaching occurred even when the bacteria were present. Rosenberg's research team found a temperature-dependent protein produced by the bacteria that enables it to stick to the coral. Once the bacteria have stuck to the coral, it multiplies and penetrates the polyp. Inside the polyp it synthesises a toxin that inhibits photosynthesis, killing the zooxanthellae. The temperature-dependent protein explains why the bacterium can only enter and grow in the coral polyp in the warm months of the year, causing coral bleaching at that time.

This is a remarkable example of the interactions between species (coral polyps, zooxanthellae and bacteria) and their dependence on a characteristic of the physical environment (water temperature).

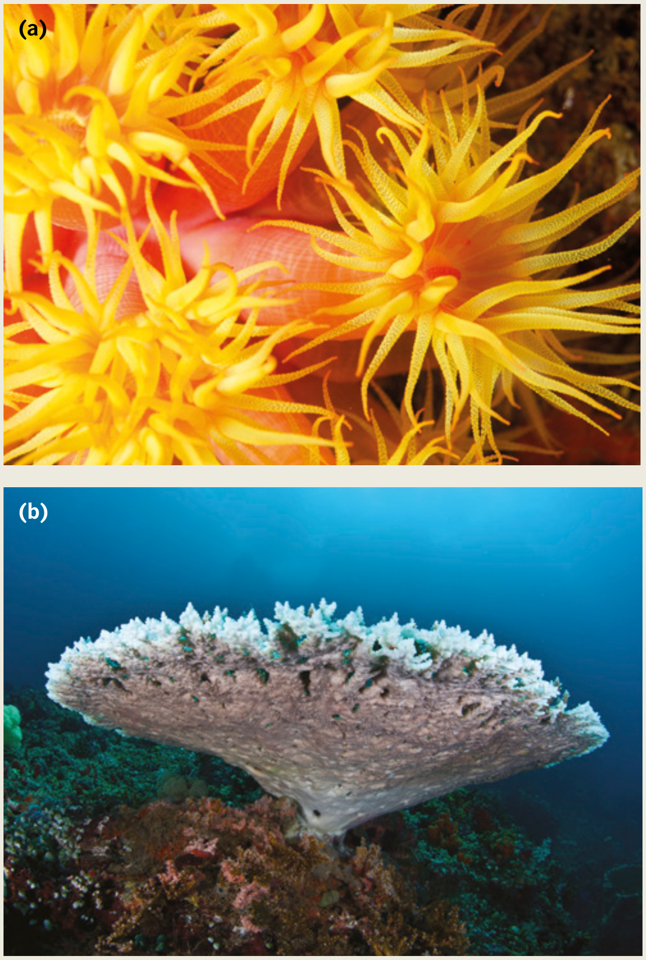

FIGURE 11.1.19 (a) Coral polyps have a mutualistic relationship with unicellular algae (zooxanthellae). The photosynthetic algae live inside the coral polyps providing them with nutrients and the coral polyps provide shelter for the algae. (b) Bleached coral. Coral bleaching occurs when the photosynthetic algae are expelled from the coral under stressful conditions. Warming ocean temperatures and bacterial infections are linked to coral bleaching.

+ ADDITIONAL

Obligate and facultative mutualism

Obligate mutualism

There are two types of mutualism: obligate mutualism and facultative mutualism. **Obligate mutualism** is when both species are completely dependent on each other for survival and reproduction. One cannot survive without the other. Many pollination relationships are examples of obligate mutualism. Yucca plants (Figure 11.1.20) rely exclusively on yucca moths to move pollen from one plant to another, and in turn the moths depend on the flowers for a safe place to hatch their eggs.

FIGURE 11.1.20 A yucca plant in Texas, USA. Yucca plants have an obligate mutualistic relationship with yucca moths.

Some species must cooperate to obtain all the nutrients they need. For example, many plants and soil-inhabiting fungi live in a close relationship called a mycorrhiza (Figure 11.1.21) where the thread-like hyphae of the fungi are very close to the outer layer of the root. Through these, the organisms transfer water, minerals, sugars and amino acids to each other. Because of the low level of nutrients such as phosphorus in many Australian soils, mycorrhizae are important for the growth of native plants.

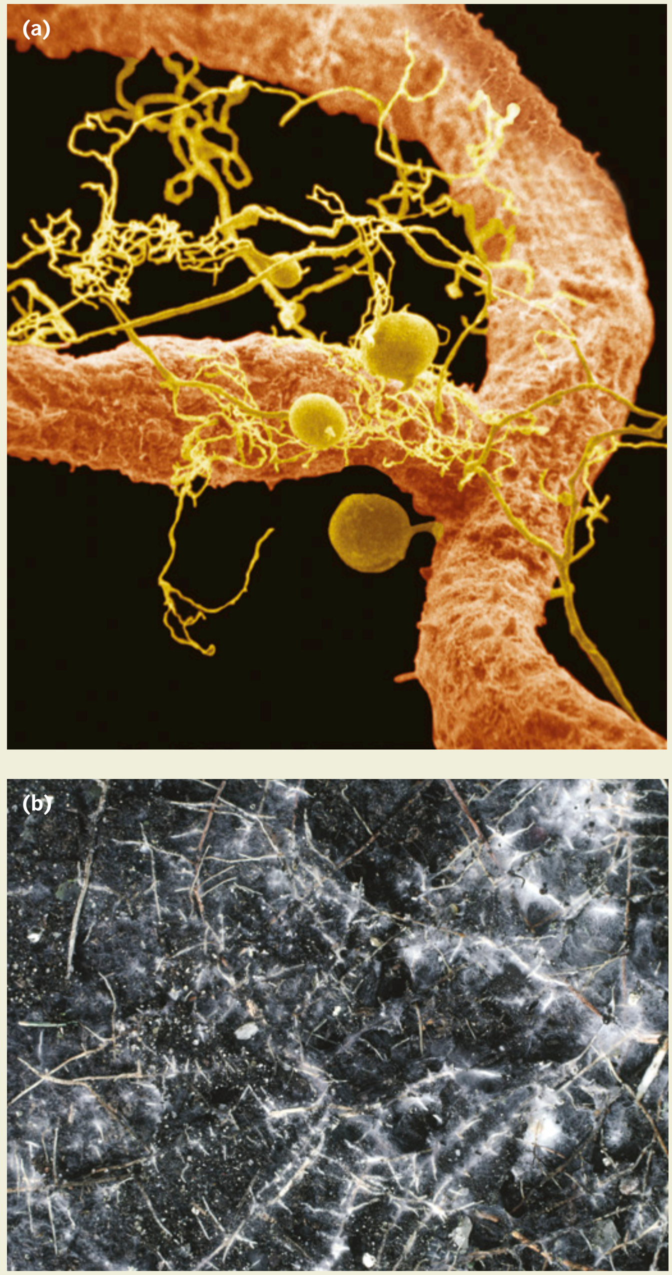

FIGURE 11.1.21 (a) An SEM of a mycorrhizal fungus (yellow-coloured fibres) on a soybean root (orange-coloured fibres). (b) Mycorrhizal (symbiotic) fungi growing in association with the roots of a small-leaved lime tree, *Tilia cordata*. Symbiotic fungi are found growing on the roots of most trees; many will not grow properly unless the appropriate fungus is present. Mycorrhizal roots take up nutrients more efficiently than uninfected roots, while the fungi obtain carbohydrates and possibly B-group vitamins from the tree. The type of symbiosis seen here is known as endotrophic mycorrhiza; the fungal hyphae (white, fluffy structures) form a mantle around the tree roots and also penetrate into the soil.

Facultative mutualism

Facultative mutualism is when both species benefit from interacting but do not rely on each other for their survival. This is sometimes called 'proto-cooperation'.

Some species are able to rid themselves of harmful parasites through facultative mutualism. For example, tick-birds and oxpeckers (Figure 11.1.22) stand on cattle or other large animals and feed on the parasites in the hair and on the skin of their host. The birds benefit from easy access to their food source and the larger animals benefit by having their parasites removed.

FIGURE 11.1.22 A yellow-billed oxpecker (*Buphagus africanus*) cleans ticks from a giraffe (*Giraffa camelopardalis*).

Pollination can be facultative mutualism because a plant may rely on several species for pollination, and the pollinators may visit many plants for their needs. Bees are the most numerous insect pollinators (Figure 11.1.23). They usually visit a number of plant species to collect nectar and pollen, which are used as food for adults and larvae. As bees move from flower to flower they transfer pollen, enabling the plants to reproduce.

FIGURE 11.1.23 The honeybee (*Apis mellifera*) is a common insect pollinator that has a facultative mutualism with many plants.

In a similar way, animals sometimes help plants by inadvertently carrying their seeds and dispersing them in new areas. This is an advantage to the plant because it reduces competition between the existing and new plants as they grow. Animal dispersal also propagates plants to new areas, promoting survival of plant species which the animals may rely on for food. In Queensland rainforests, the southern cassowary (Figure 11.1.24) is essential for spreading the seeds of some plants, such as the cassowary plum (*Cerbera floribunda*). It feeds on the fruits and transports the plant seeds elsewhere. The seeds are then excreted intact, and the bird's droppings act as a ready-made fertiliser.

FIGURE 11.1.24 The southern cassowary (*Casuarius casuarius*) disperses the seeds of many plants that bear fruit by ingesting the seeds and depositing them elsewhere.

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Commensalism or mutualism?

The relationship between clownfish and sea anemones is often said to be commensalism (Figure 11.1.25). The clownfish gains protection in the stinging tentacles and the sea anemone appears not to benefit. However, as the clownfish feeds, small bits of food come in contact with the tentacles and the sea anemone may feed on this. So there is a slight positive benefit to the sea anemone, making this a case of mutualism rather than commensalism.

FIGURE 11.1.25 Three clownfish sheltering within sea anemones. The relationship is mutualism rather than commensalism because both species benefit.

BIOFILE CCT

Mutualism and the honeyguide bird

The 1974 film *Animals Are Beautiful People* popularised the idea that the African greater honeyguide bird (*Indicator indicator*) leads the honey badger (*Mellivora capensis*) to wild beehives (Figure 11.1.26). Scientists who have studied the behaviour of these animals suggest that this is extremely unlikely.

However, there is a proven relationship between honeyguide birds and humans, which has probably evolved over thousands of years. The bird gives a distinctive call that indicates it knows the location of a beehive. Humans have learned to recognise this call, and follow the bird when it flies off. When the bird reaches the hive it perches low in a tree, then waits for the humans to break open the hive. The humans get the honey, and the bird gets to feed on the beeswax and bee larvae left behind.

FIGURE 11.1.26 The belief that the African greater honeyguide bird (*Indicator indicator*) leads honey badgers (*Mellivora capensis*) to beehives is probably false. However, humans and the honeyguide bird do have a mutualistic relationship, with the honeyguide leading humans to beehives.

Benign interactions

Benign interactions are interactions in which no species is harmed.

Commensalism

Commensalism is an interaction between species in which only one species benefits but the other species is not affected. Animals such as birds or possums nesting in a tree hollow is an example of commensalism. In this case, the bird or possum benefits and the tree is not harmed (Figure 11.1.27).

FIGURE 11.1.27 Many owl species nest in tree hollows where it is relatively safe during the day. This is an example of commensalism, because the owl benefits and the tree is not harmed.

Trees are also often host to epiphytes: smaller plants such as orchids, ferns, mosses, liverworts and lichens that live on the trunk or in the crown of the tree (Figure 11.1.28). The epiphyte receives sunlight and rainwater. This relationship is usually benign for the tree because it is neither helped nor harmed (unless it becomes overloaded with the weight of the epiphytes on its branches).

Harmful interactions

Harmful interactions are those in which only one species benefits and the other species is harmed as a result of the interaction.

Parasitism

In parasitism, one species (the **parasite**) benefits and the other species (the **host**) is harmed. Ectoparasites such as ticks and mistletoes live on or outside the host (Figure 11.1.29). Endoparasites such as parasitic fungi and wood-borers live inside the host (Figure 11.1.30). A parasite obtains its food from the host but does not necessarily kill it. The type of harm the parasite causes the host varies, but may include the following effects:

- shortened lifespan
- impaired functions such as digestion, photosynthesis or reproduction
- less ability to withstand stresses such as drought or cold
- greater vulnerability to predators.

Many parasites have more than one host during their life cycle. A host that transfers a parasite to another host is called a vector. For example, the malarial mosquito is a vector for the *Plasmodium* parasite. It transfers the parasite when it bites a person to obtain blood. An infected person is also a vector for *Plasmodium* because they transfer the parasite to the mosquito when it bites them.

All organisms have parasites. For example, every species of plant and animal that has been studied has been found to have at least one parasitic species living in it. Tapeworms are a common parasite in animals (Figure 11.1.31). They are ingested and then attach to the small intestine, where they absorb nutrients and can grow quite large. Although they can cause illness, loss of appetite and anaemia, they sometimes produce no symptoms at all.

Amensalism

Amensalism refers to an association between species in which one is inhibited or killed and the other species is unaffected.

A simple model of amensalism is the way in which animals can inadvertently damage vegetation around them but are unaffected by the relationship. For example, animals such as sheep and cattle often trample grass. The grass may be damaged or killed, but the animals receive no benefit from having done so (Figure 11.1.32a). Similarly, some waterbirds such as cormorants kill vegetation in places where they roost or nest (Figure 11.1.32b). This is because their droppings are high in nitrogen, phosphate and potassium, which plants cannot tolerate.

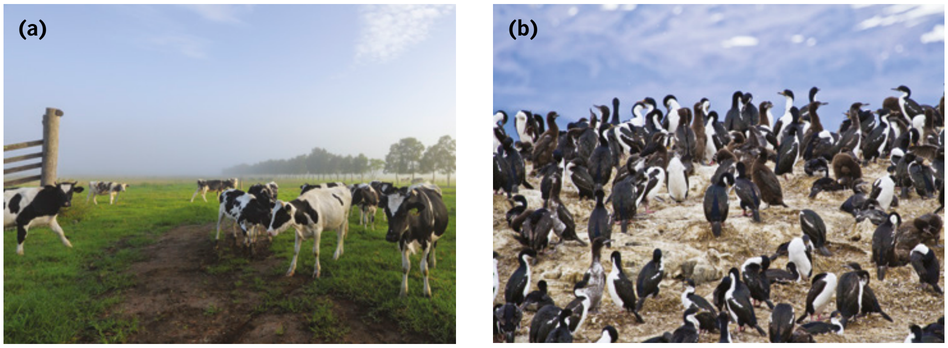

FIGURE 11.1.32 (a) Larger animals such as sheep and cattle trample and damage grass, but are unaffected by the relationship. (b) Cormorant droppings can kill vegetation, but this does not benefit the birds. Both these interactions are forms of amensalism.

FIGURE 11.1.28 Epiphytes form a commensal relationship with the tree they grow on.

FIGURE 11.1.29 Mistletoes are ectoparasites; they grow on other plant species and take nutrients and water from them.

FIGURE 11.1.30 This stick insect has been invaded, and is being killed, by a parasitic fungus. The fruiting bodies of the fungus are erupting from the insect's body and will release spores that help the parasite to spread.

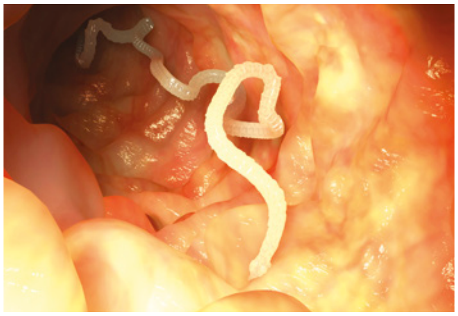

FIGURE 11.1.31 Tapeworms are endoparasites that infect animals, including humans.

+ ADDITIONAL

Complex relationships: ants, plants and aphids

Many ants have developed a variety of symbiotic relationships with other invertebrates and plants. One of the most common is the herding or farming of sap-feeding insects such as aphids, scale bugs and mealy bugs.

The relationship between ants and aphids has been well studied. Home gardeners and horticulturalists are well aware of the damage done by aphids when they pierce the phloem vessels in plant stems and suck the sugar-rich fluids from the host plant. Because these liquids are low in nitrogen, aphids must consume large quantities of them to gain adequate nutrition. The aphids then need to excrete large quantities of waste, called honeydew, which has a high sugar content.

Some ants that consume this honeydew protect and cultivate the aphids to ensure the continued supply of the food (Figure 11.1.33). By stroking an aphid, an ant can induce it to release a honeydew droplet, a process known as 'milking'. The ants also care for aphid eggs, move the aphids to the best sap areas on the plant and prevent predators like ladybirds from eating the aphids.

This may seem like mutualism, benefiting both species. However, the ants control the relationship and may bite the wings off an aphid to prevent it from escaping. In addition, ants carry a chemical on their feet to mark trails and their territory; this same chemical is used by ants to tranquillise the aphids they are farming and prevent them from dispersing.

Aphids themselves have an obligate mutualism with specialist bacteria that live in certain cells in the aphid. The bacteria, which are passed down from aphid parent to offspring, provide essential amino acids that are lacking in plant sap.

Aphids are also parasitic on the plants, disrupting the supply of sugary sap carried in the phloem. While the ants do not damage the plants directly, they protect aphids and other sap-sucking insects that do. Because honeydew is sugar-rich it encourages the growth of sooty mould, a black fungus that is destructive to plants.

FIGURE 11.1.33 An ant tends a group of aphids so they will produce honeydew for the ant to eat.

FEEDING INTERDEPENDENCIES

FIGURE 11.1.34 When the scarlet honeyeater (*Myzomela sanguinolenta*) gathers nectar from grevillea flowers, it transfers pollen from one flower to another.

One important way that species interact and apply selection pressures on one another in an ecosystem is through feeding relationships. For example, a leaf-eating insect is part of the environment of a grevillea shrub. The insect has a source of food and benefits from the interaction, but the shrub is harmed because its photosynthetic leaf area is reduced. On the other hand, a honeyeater (Figure 11.1.34), which is another part of the environment of the shrub, is not harmful but useful to the tree. As the bird gathers nectar from the grevillea flowers, it transfers pollen from shrub to shrub. The interaction benefits both organisms. The bird pollinates the grevillea and gathers its reward as food. Having a diverse range of species that includes both harmful and helpful organisms for the grevillea means that the ecosystem remains balanced.

Species form a web of **feeding interdependencies** within an ecosystem. Any change to one species within an ecosystem will have a flow-on effect on other species in the same food web. Feeding interdependencies make species vulnerable to changes in their ecosystem. Ecosystem changes can present new selection pressures that may cause the extinction of species or lead to organisms adapting to the new conditions. The giant panda (*Ailuropoda melanoleuca*) is an example of a species that is especially vulnerable to environmental change because of its specialist diet (Figure 11.1.35).

All organisms in an ecosystem require energy to survive. Some organisms can create their own food (**autotrophs**), but others need to consume specific types of food from a particular environment (**heterotrophs**). Some organisms feed on plants, some feed on insects or other animals, and others feed on dead and decaying material. Almost all organisms are consumed by at least one other organism.

FIGURE 11.1.35 The giant panda (*Ailuropoda melanoleuca*) is a native of China and is a specialist feeder on bamboo. It needs to eat about 10 kg of various types and growth stages of bamboo plants a day. Such a specialist diet has made the panda very vulnerable to habitat destruction.

Species in an ecosystem are interdependent; that is, they rely on each other. If one species is removed from an ecosystem, any species that interacted with it is affected. For example, sea otters along the coasts of the northern and eastern North Pacific Ocean feed on sea urchins and keep the sea urchin numbers in balance. If sea otters were suddenly removed from the ecosystem, sea urchin numbers would increase, and the kelp that the urchins feed on would be overgrazed (Figure 11.1.36).

The removal of a species may have a positive effect or a negative effect on other species in the ecosystem. Likewise, a species being added to an ecosystem can also have far-reaching effects. By understanding the relationships within an ecosystem, the impact of introducing or removing species can be predicted. For example, studying the feeding relationships between organisms in an ecosystem can help scientists understand why some species are affected by such changes. This understanding then allows the scientists to predict the effects of ecosystem changes, assisting them in the management and **conservation** of populations, species and ecosystems.

FIGURE 11.1.36 Sea otters (*Enhydra lutris*) have a feeding relationship with sea urchins which is important for ecosystem balance in the northern and eastern North Pacific Ocean.

BIOLOGY IN ACTION S

Living in a eucalypt

A eucalypt tree is home to a variety of organisms. Each part of the tree acts in effect as a microhabitat. Some organisms live and feed among the leaves and branches in the crown of the tree. Some organisms live in the bark or on the trunk. Other organisms live at the base of the tree and among the accumulated litter of dead leaves and fallen bark. Seed-harvesting ants take seeds that fall to the ground. Some organisms live out of sight among the tree's roots. Animals come and go from the tree. Some are active only during the day and others are active only at night.

The canopy provides food for many animals. The leaves of some eucalypts are food for koalas (Figure 11.1.37). Insect larvae also eat the leaves. The ringtail possum feeds on leaves and flowers. Small species of gliding possum eat nectar and pollen at night, and honeyeaters eat nectar during the day. Parrots such as rosellas crush the woody eucalypt fruits to eat the seeds inside.

Spots on eucalypt leaves are evidence of fungi that break down leaf tissue for food. Tumour-like growths on the trunk are evidence of other fungi growing in the wood. Lichens and plants such as mosses, ferns and orchids use the trunk of the tree for support.

The smaller animals that eat the leaves and flowers are hunted by larger animals. The yellow-bellied glider mainly eats insects. Leadbeater's possum, which inhabits only mountain ash trees, catches tree crickets hiding in the bark. Spiders weave webs to catch their prey. Skinks feed on insects, and are themselves food for the sharp-eyed kookaburra.

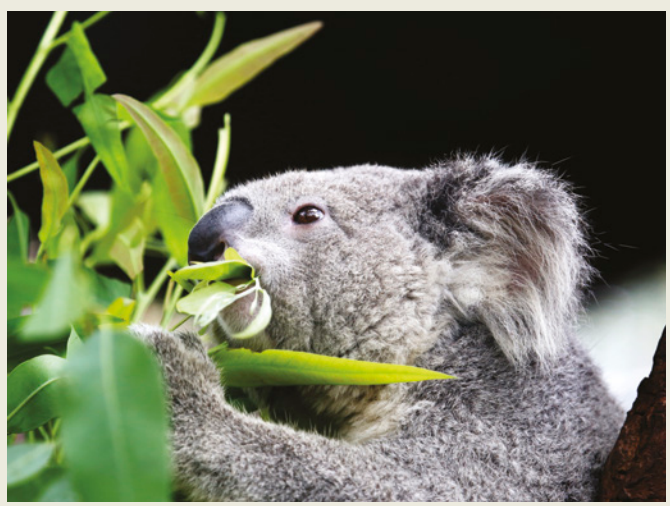

FIGURE 11.1.37 Manna gum (*Eucalyptus viminalis*), swamp gum (*Eucalyptus ovata*) and river red gum (*Eucalyptus camaldulensis*) are the home of the koala, which eats the leaves of a restricted number of eucalypt species.

Food chains

A **food chain** links organisms according to their feeding relationships. The two main groups of organisms in a food chain are **producers** (also known as autotrophs) and **consumers** (also known as heterotrophs). The energy that producers (plants) make using photosynthesis may be eaten by a consumer, which may be eaten by another consumer, and so on. In this way, the energy in organic matter is transferred between organisms.

In a food chain diagram (Figure 11.1.38) the arrows show the flow of energy and matter through the chain. In a eucalypt tree, kookaburras feed on skinks that feed on insects that feed on the eucalypt leaves. This is an example of a food chain with three links between four types of organisms. In the pond food chain discussed later (Figure 11.1.40) there is just one link pictured: the link between the catfish and the parasites that feed on them.

A food chain is a series of organisms linked by their feeding relationships.

Producers are autotrophs and the first link in a food chain. All other organisms are heterotrophic consumers.

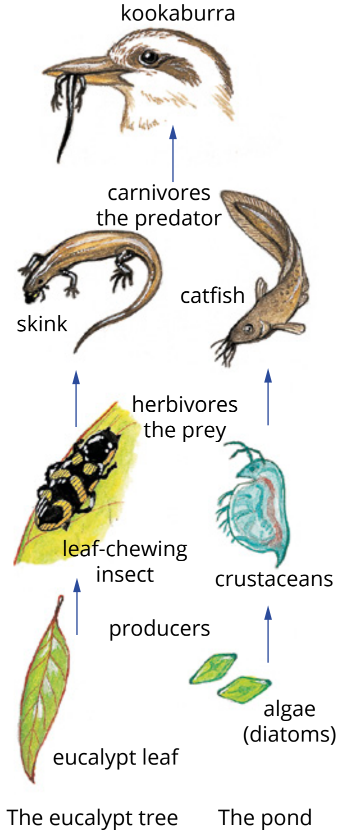

FIGURE 11.1.38 Two simple food chains: one in a eucalypt tree and one in a pond. The direction of the arrows indicate the transfer of energy from one organism to another through feeding.

Food chain participants

Producers

Plants and algae in a pond, and a eucalypt tree in a forest, play an important role as the first links in food chains. They manufacture their own food by photosynthesis, so they are autotrophs. In food chains and food webs, autotrophs are called producers. Producers are always the first link in a food chain because they produce organic compounds from simple inorganic compounds. There are two types of autotrophs: photosynthetic autotrophs and chemosynthetic autotrophs.

Most producers, including plants and algae, are photosynthetic autotrophs (Figure 11.1.39). They use photosynthesis to make their own food. Some specialist autotrophs are chemosynthetic. This means they obtain their energy for producing organic compounds directly from inorganic molecules such as hydrogen sulfide and methane. Autotrophs are examined in detail in Chapter 5.

FIGURE 11.1.39 Plants are photosynthetic autotrophs. They are often the first link in a food chain.

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Consumers

All organisms that are not producers are consumers. They are heterotrophs; that is, they obtain their energy by consuming other organisms. There are six types of consumers:

- herbivores
- carnivores
- parasites
- scavengers
- detritivores
- decomposers.

Consumers are further classified as primary, secondary, tertiary or quaternary depending on where they fit into a food chain. In the eucalypt tree, insects that eat the leaves are primary or first-order consumers; skinks that eat the insects are secondary or second-order consumers; and the kookaburra that eats the skink is a tertiary or third-order consumer. If there is no other carnivore to consume it, the kookaburra is the top carnivore.

Consumers can be classified according to the type of organisms they feed on and the ways in which they feed on them. The different classifications are shown in Table 11.1.2 (page 510), with examples of each type.

Predator–prey food chains

Many food chains are **predator–prey food chains**. A simple example from a pond is the catfish that feeds on crustaceans (*Daphnia*) that feed on algae (diatoms). The food chain linking the kookaburra, skink, insect and eucalypt tree (Figure 11.1.38) is also an example of a predator–prey food chain.

Predators usually eat prey smaller than themselves. A hawk preys upon animals the size of a mouse or small rabbit. Predator–prey food chains usually proceed from small organisms to large organisms.

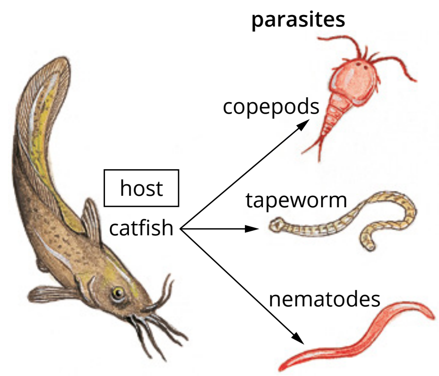


FIGURE 11.1.40 Parasite–host food chains in the pond. The food chains go from the larger host, the catfish (*Tandanus tandanus*), to smaller organisms, the parasites.

Parasite–host food chains

Parasite–host food chains look a little different from predator–prey food chains. Parasite–host food chains have a large organism (the host) as a source of food for a smaller organism (the parasite). Figures 11.1.40 and 11.1.41 are examples of parasite–host food chains in aquatic ecosystems.

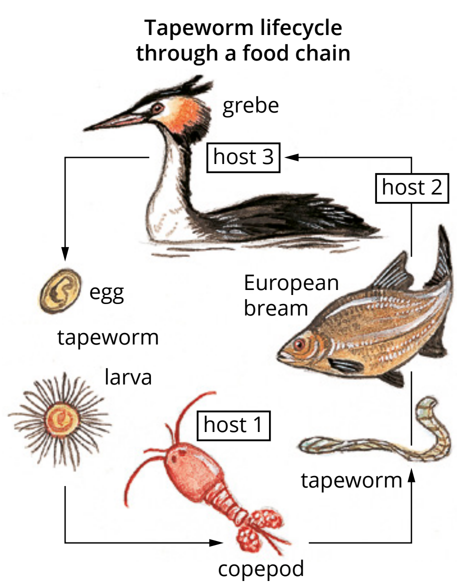
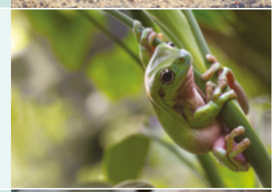
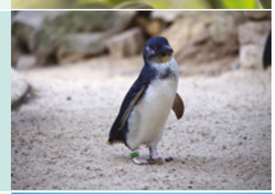
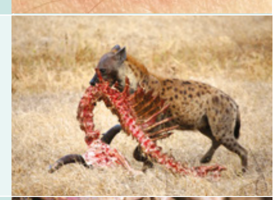
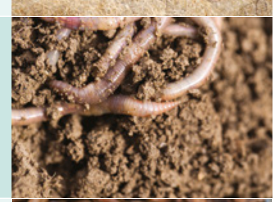
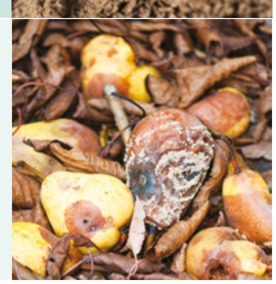


FIGURE 11.1.41 The life cycle of a tapeworm through an aquatic food chain

TABLE 11.1.2 Types of heterotrophic consumers

Name	Description	Examples
herbivores	Herbivores feed on plants and other producers.	• catfish • swan • psyllid insect • koala • honeyeater • blue whale • giraffe (pictured) 
carnivores	Carnivores consume other consumers. Carnivores that catch live prey are called predators.	• quoll • meerkat (pictured) • dingo • eagle • panther 
	Carnivores that feed directly on herbivores are secondary consumers (also known as first-order carnivores).	• dragonfly nymph • skink • frog (pictured) • sea star 
	Carnivores that feed on secondary consumers are tertiary consumers (also known as second-order carnivores).	• tuna • snake • penguin (pictured) • goanna 
	Carnivores that are the last link in the food chain are quaternary consumers (also known as third-order consumers and top consumers or top predators).	• crocodile • kookaburra • great white shark (pictured) • anaconda 
parasites	Parasites live and feed on the surface of or from inside other organisms (known as the host), causing them harm. At different stages of development, from larva to adult, the parasite may feed on a different host species.	• heartworm • tick (pictured) • malarial mosquito • liver fluke 
scavengers	Scavengers consume other dead animals.	• vulture • Tasmanian devil • planarian (flatworm) • hyena (pictured) 
detritivores	Detritivores feed on non-living organic material including fruits, remains of dead plants and animals, and also waste that accumulates as detritus. Detritivores are important because they physically break down organic material into smaller pieces.	• millipede • earthworm (pictured) • hermit crab • dung beetle 
decomposers	Decomposers break down (decompose) and then consume non-living organic material. They secrete enzymes over the non-living organic material, breaking it down into inorganic compounds (such as carbon dioxide, nitrogen and phosphate). Some of these inorganic compounds are absorbed by the decomposer—organisms that feed in this way are called saprotrophs. Some compounds escape into the environment, including the pond water, soil and air. Here, the inorganic compounds are then available to producers as nutrients, and the food cycle is closed. This makes decomposers the last link in food chains.	• bacterium • fungus (pictured) 

The **life cycle** of many parasites is complex. At different stages of development, from larva to adult, each feeds on a separate host species. Thus one species of parasite may be linked to a number of food chains. In Figure 11.1.41 the tapeworm *Ligula intestinalis* feeds on three hosts. An egg of the tapeworm hatches in the water. A copepod (first host) eats the larva. The larva grows in the intestinal cavity of the copepod after penetrating the intestinal wall. The copepod is eaten by a fish (second host) such as a bream, and continues to develop and grow in the intestine of the fish. An aquatic bird (third host), such as a grebe, then eats the fish. The adult tapeworm develops within two days of being eaten because of the higher temperature in the bird's intestine. Before they die in the bird, the adult worms produce eggs which pass out into the water, and the cycle continues.

Detritivore–decomposer food chains

In temperate forests only about 10% of the plant material is eaten directly each year by herbivores. Much of the plant material falls as leaf litter. Dead leaves, dead branches, fallen tree trunks, dead roots in the soil, and the remains of dead animals are a major source of food for **detritivores** such as snails, worms, termites, springtails, millipedes and mites, and **decomposers** such as fungi and bacteria. Detritivore and decomposer food chains are most abundant in forests (Figure 11.1.42). They are also important in aquatic ecosystems where **detritus** (organic waste material) builds up on the bottom of a pond, lake or bay (Figure 11.1.43).

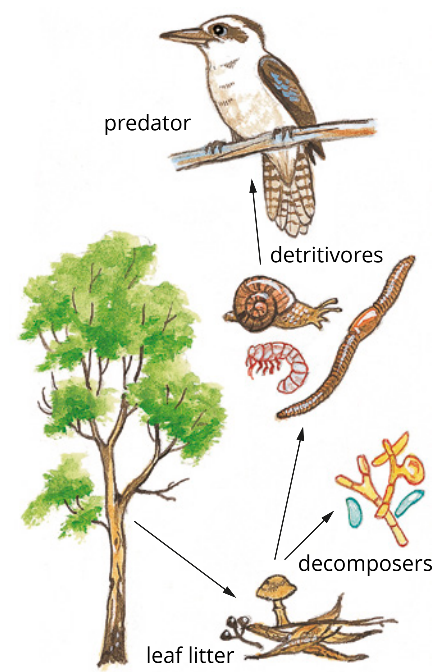


FIGURE 11.1.42 Detritivore and decomposer food chains are very important in terrestrial ecosystems, where plant litter accumulates on a forest floor.

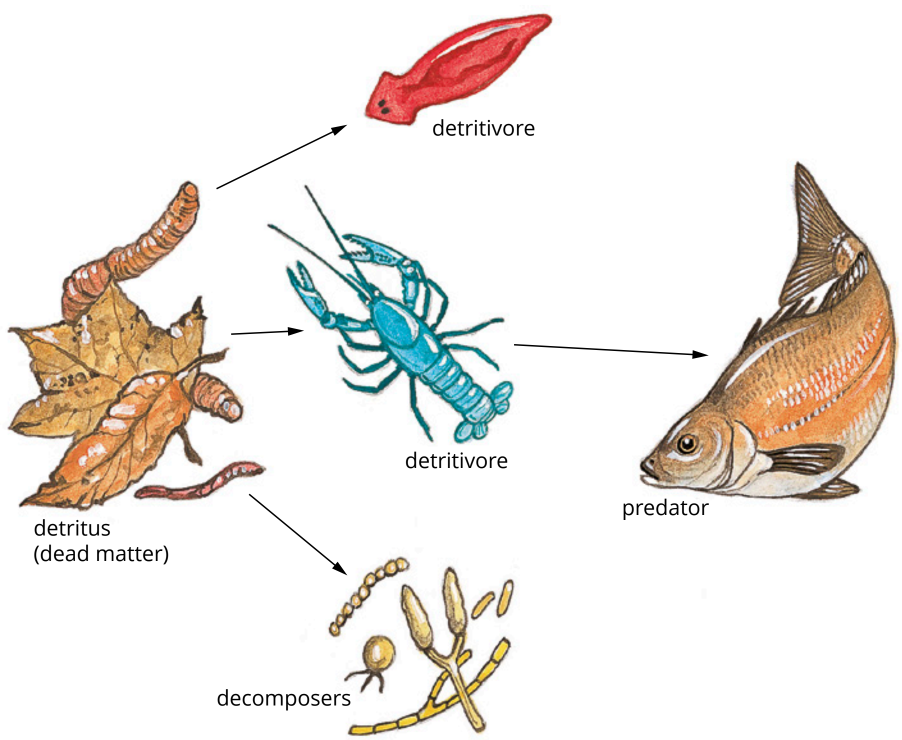


FIGURE 11.1.43 Detritivore and decomposer food chains in the pond both start with dead matter.

Detritivores and decomposers are organisms that consume dead organisms. Detritivores break down organisms into small particles, which decomposers then break down further into organic and inorganic nutrients.

As a detritivore eats dead leaves, it also eats decomposers (bacteria and fungi) that are on and in the dead leaves. The detritivore also has symbiotic gut bacteria (microflora), distinct from the habitat microflora, which enables it to digest cellulose and other plant matter.

Detritivores are important because they physically break down plant litter into small particles. Parts of the dead leaves that a detritivore chews pass out of the animal as faecal pellets. These smaller particles are then easier for decomposers to consume. Some detritivore animals also eat faecal pellets (either their own or those of other species). Fly and beetle maggots are two examples of animals that consume faeces and dead organisms.

The decomposers, bacteria and fungi, are the last link in this chain of eating, re-eating and breaking down detritus. The digestive enzymes that decomposers secrete break down the organic matter into soluble organic molecules such as sugars and amino acids, and eventually into inorganic nutrients such as carbon dioxide and phosphate. Some of these products are absorbed by decomposers and some remain in water, soil or the air.

Decomposers

Decomposers are the final link in the cycle of matter in ecosystems. They are able to use the materials left by all the other organisms in a food chain. All organisms eventually die, leaving carcasses. They also discard matter such as dead skin, undigested food, leaves and dead branches while they are alive. In the examples shown in Figure 11.1.44, the cabbage sheds its leaves after blooming, and all animals regularly deposit faeces.

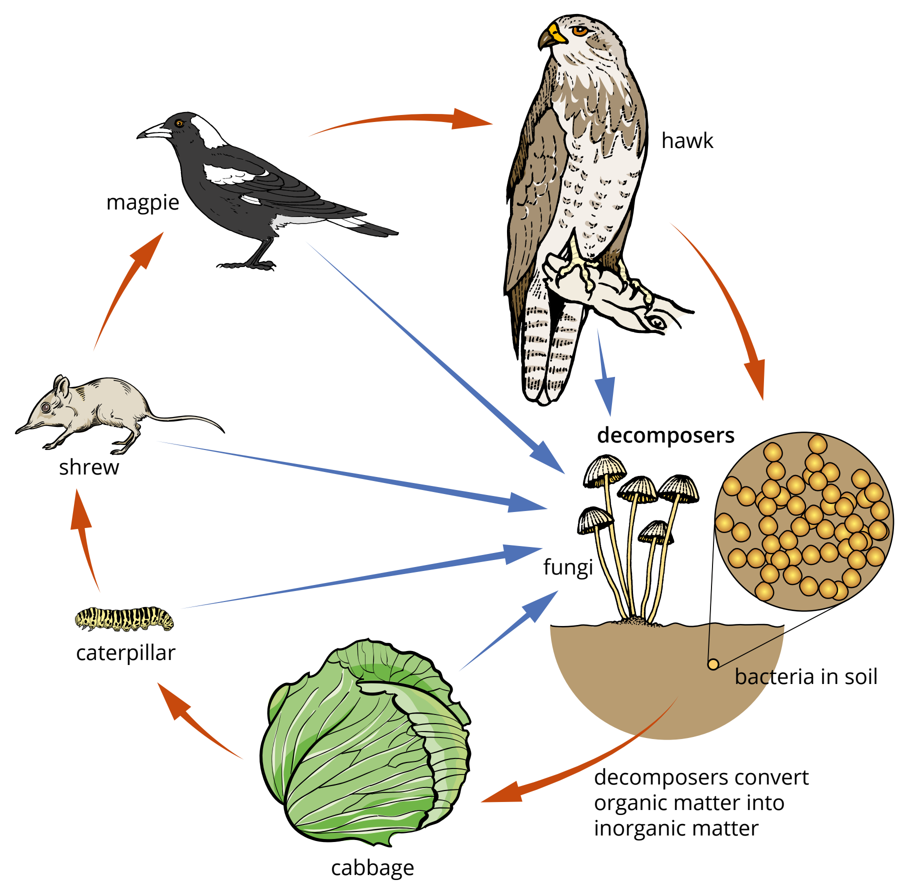


FIGURE 11.1.44 Decomposers complete the cycle of inorganic matter.

Decomposers can use these materials and transform them into simple inorganic compounds such as carbon dioxide, water, hydrogen sulfide and ammonia. These compounds can then be used by autotrophs. In this way, decomposers complete the cycle of matter. The inorganic matter taken up by autotrophs goes through producers and consumers and decomposers and back to inorganic matter.

BIOFILE S

Dung for dinner

A lot of land in Australia is devoted to sheep and cattle agriculture. This has led to excessive amounts of sheep and cattle dung in arid and semi-arid environments. The dung dries out before it can be broken down, and fungi and bacteria might only be active during wetter periods. As a result, the dung accumulates on the ground surface and is a breeding ground for bush flies and other types of flies.

Dung beetles are detritivores that bury faeces to conserve the moisture content before they eat them (Figure 11.1.45). Native dung beetles have evolved to consume the smaller faeces of native animals, but they are ineffective in burying and consuming large dung pads in grazing lands. Over 50 species of dung beetles, such as the elephant dung beetle, have been introduced into Australia from other countries in an attempt to reduce the accumulation of cattle dung and reduce the fly population.

FIGURE 11.1.45 Dung beetles bury fresh dung underground, where it will remain moist for consumption by the beetles later or will become part of a decomposer food chain. Bacteria and fungi will break down this organic matter, some of which they will use for themselves and some of which will be recycled into the environment.

Food webs

Most organisms are part of more than one food chain because they eat or are eaten by more than one type of organism. Because these food chains are linked, they form a complex system of feeding interactions called a **food web** (Figure 11.1.46).

Food webs are formed by linking up food chains.

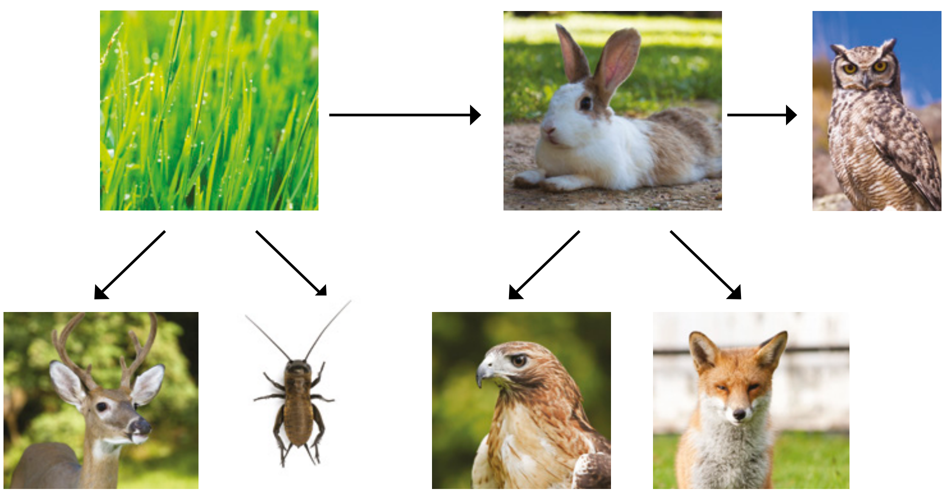


FIGURE 11.1.46 A simple food chain is a small part of the entire set of feeding relationships in an ecosystem. In this diagram, you can see that a food chain can be turned into a food web by linking feeding relationships.

Simple food chains in which the organisms have only one food source are rare in nature. A plant is usually eaten by several herbivore species. Herbivores that feed on just one plant species are rare. Predators, even those that are specialised for catching and feeding on one type of animal, can adapt to a different kind of prey if the animals that they normally hunt are in short supply. An example of a predator that has done this is the wedge-tailed eagle (*Aquila audax*) shown in Figure 11.1.47. As the diets of species become broader, the food web becomes more complex.

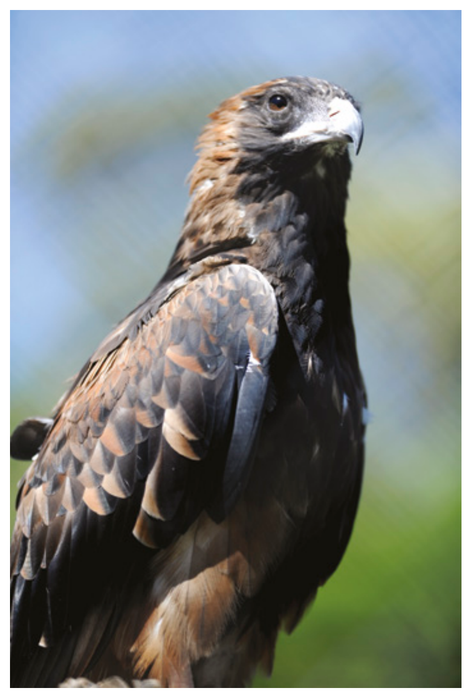


FIGURE 11.1.47 The wedge-tailed eagle (*Aquila audax*) is a predator that can prey on a variety of animals. Before Europeans arrived in Australia, the eagle's diet was probably only reptiles and small mammals. Today its diet is mainly introduced rabbits and hares, although it continues to eat native animals.

The complexity of the food web gives an ecosystem its stability. In a simple food chain, the removal of one species (i.e. one link) is likely to have a disastrous effect on other organisms. The loss of one species from a complex web has less effect, because alternative food sources are usually available. For example, the giant panda's food web is really one simple food chain of two species: bamboo and the giant panda. The simplicity of this food chain makes the giant panda vulnerable because it only has one food source.

Trophic levels

Each feeding level in a food chain or web is called a **trophic level**. All the producers in a typical food chain or web make up the first trophic level. Herbivores (primary consumers) are at the second trophic level because they feed on the producers from the first level. Secondary consumers, which feed on herbivores, are at the third trophic level, and so on. You can see these roles labelled in the food chain in Figure 11.1.48.

Food chains are usually short, often with only three or four links (trophic levels). Insect- and detritivore-dominated food webs may have up to six levels. For example: plant litter (detritus) → springtail → mite → ant → skink → cat.

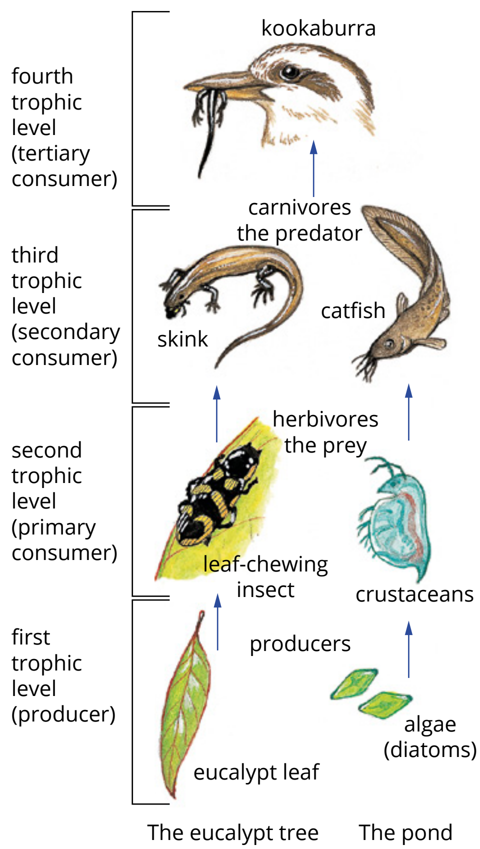
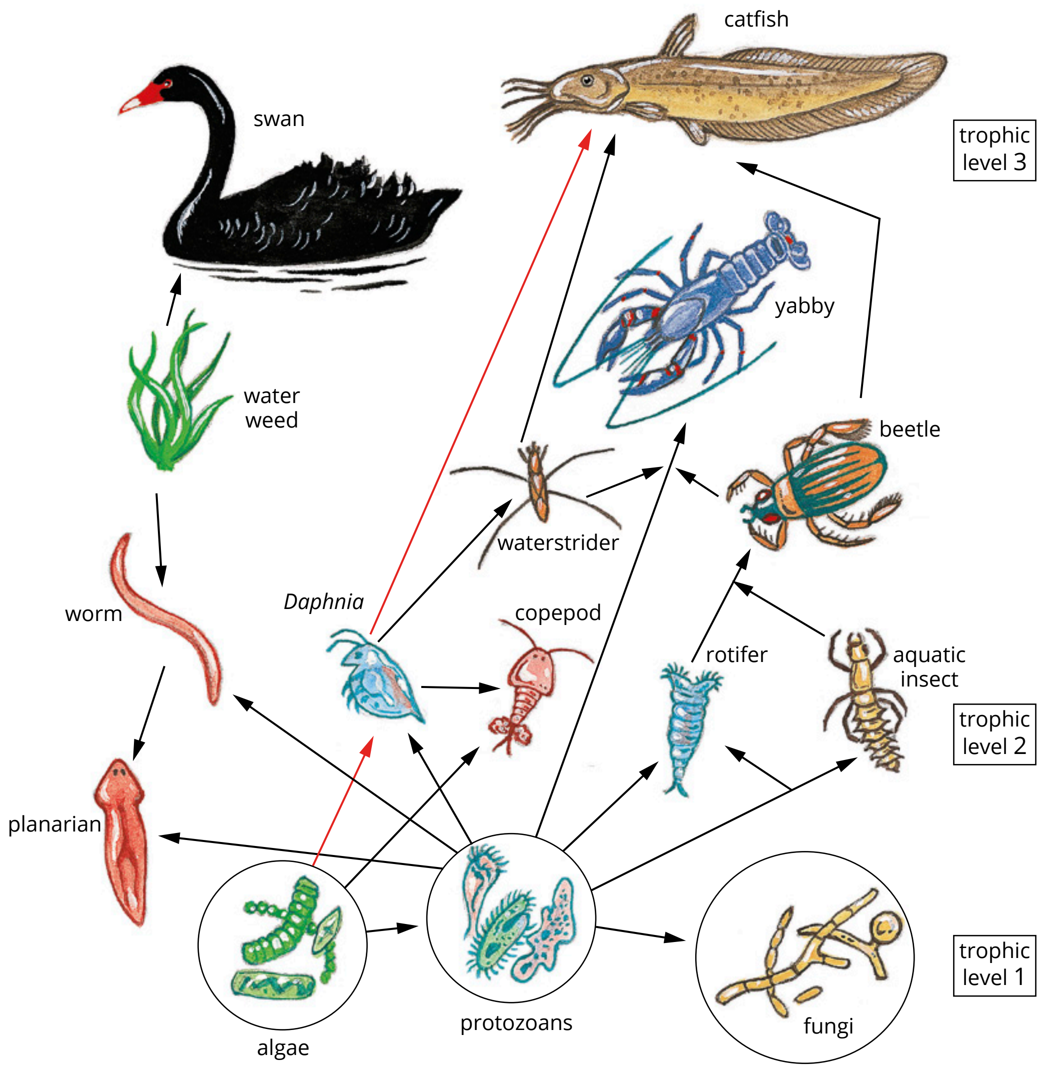


FIGURE 11.1.48 The trophic levels in food chains

An organism may function at more than one trophic level in a food web. In the example of the pond food web in Figure 11.1.49, the catfish feeds on small crustaceans and insects, as well as snails and small fish. The catfish is a secondary consumer at the third trophic level because it eats *Daphnia* (also called water fleas) and a tertiary consumer at the fourth trophic level because it eats water striders that eat *Daphnia*.



WS 4.3

FIGURE 11.1.49 The food web for a freshwater pond. A food web diagram represents feeding relationships in an ecosystem. The chain of red arrows illustrates three different trophic levels. The direction of arrow represents the direction of energy flow in the food web.

+ ADDITIONAL

Ecological detectives: analysing diets in food webs

How do ecologists find out what an animal eats, so they can work out a food web?

Direct observation

Field ecologists often watch animals feeding and note what they eat. A checklist of plants in the area can be used to work out the different species eaten by herbivores.

Scats and pellets

Heads, legs and wings of insects, bone, teeth, skin, eggshells, feathers, seeds and indigestible plant parts can be identified in the faeces and pellets of many animals (Figure 11.1.50a, b). Studying faeces of large herbivores, and birds and mammals that eat insects, is especially successful. Faeces, also called scats, can be found on the ground and in nests and burrows (Figure 11.1.50c). Their shape and colour can often be used to tell what animal it came from. Regurgitated pellets that contain indigestible bones and feathers of owl prey can be used in the same way. Thus, inspection of roosting sites can reveal what a bird has eaten.

Stomach contents

Inspecting stomach contents is a direct method of determining diet. Stomachs of birds can be pumped or flushed with saline solution, and the stomachs of dead animals such as trawled fish and road kills can be dissected to reveal the contents. Food may be found whole or in parts. Hard parts such as bone, fish scales, fur and seeds are often characteristic of species.

Exclusion experiments

Ecologists can determine what species of plants herbivores prefer to eat by exclusion experiments. A plot of vegetation is fenced to exclude the herbivore. The species of plants that grow in the plot are compared with the grazed area outside the fence. The differences between the grazed and ungrazed areas indicate which plant species have been grazed by the herbivore.

DNA analysis

In some cases, DNA analysis can be used to identify fragments of organisms in stomach contents, faeces or pellets. However, this analysis can be time consuming and expensive.

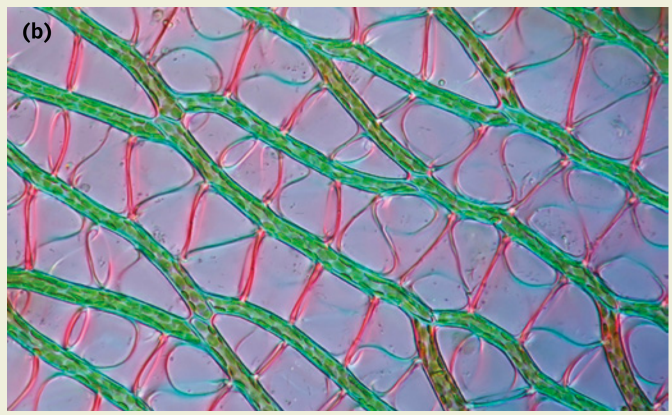




FIGURE 11.1.50 (a) Cassowaries eat up to 150 species of rainforest fruits. They eat the fruit whole, and their large piles of droppings contain undigested seeds that can be identified. (b) The cells of sphagnum mosses are so different from any other plants that they can be recognised among undigested food even if there are only a few cells. (c) The size and shape of scats from animals such as koalas, wombats (pictured) and kangaroos can be used to work out the animal they came from.

11.1 Review

SUMMARY

- Changes to environmental conditions on Earth result from events such as ice ages and from processes such as tectonic plate movement.
- Climate affects and determines ecosystem functioning as well as species' presence, behaviour and interactions.
- Biogeography is the study of organism distribution and the factors favouring species abundance in an ecosystem.
- Interactions between different species are known as interspecific interactions.
- Interactions between species can be oppositional (e.g. competition and predation) or can involve organisms working together (symbiosis).
- Symbiosis can be beneficial, neutral or harmful to the organisms involved.
- Types of symbiosis are mutualism, commensalism, parasitism and amensalism.
  - Mutualism benefits both organisms. If the organisms depend on each other for survival, it is called obligate mutualism. If they help each other but are not dependent on each other, it is called facultative mutualism.
  - Commensalism is a benign interaction in which one organism benefits and the other organism is unaffected by the interaction.
  - Harmful interactions are those in which one organism is harmed. Parasitism and amensalism are examples of harmful interactions.
  - In parasitism, one organism (the parasite) benefits, living in or on the other organism (the host), which is harmed.
  - Amensalism is an interaction in which one organism is inhibited or killed and the other is unaffected.
  - Predation is an interaction in which one animal species (a predator) feeds on another animal species (its prey). The predator benefits and the prey is harmed.
- Different species are interconnected in their ecosystem through feeding relationships. These relationships form linear food chains and branching food webs.
- Food chain diagrams are linear diagrams that show the flow of energy and matter through each trophic level, starting with a producer.
- Producers are autotrophic organisms; they can produce their own organic matter. They are the first trophic level in a food chain or web.
- All other organisms are consumers (heterotrophs), which consume other organisms to obtain organic matter.
- There are different types of food chains, called predator–prey, parasite–host or detritivore–decomposer food chains depending on the relationships between organisms.
- Decomposers, including bacteria and fungi, are the last link in food chains because they break down food to inorganic compounds, which can then be taken up by producers.
- Food chains link together into food webs and this complexity of relationships provides an ecosystem with stability.
- Complex food webs are more stable than simple food webs.
- Each level in a food chain or web is called a trophic level. A species may function at more than one trophic level in a food chain or web.

KEY QUESTIONS

1 How do the following processes shape ecosystems?
  a ice ages
  b tectonic plate movement

2 Explain what a climatic zone is, and how the latitude of a land mass determines its climate.

3 Explain the term biogeography and give an example of an ecosystem biogeographers have studied.

4 What is biodiversity, and how does it vary between ecosystems?

5 Compare and contrast the two types of mutualism. Use that information to identify the type of mutualism that exists between a plant being pollinated by an insect, when the plant has other potential pollinators.

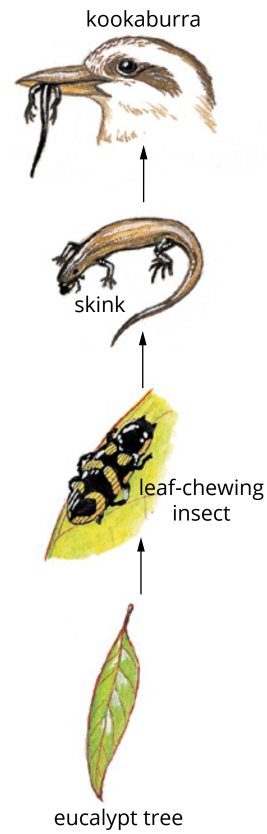
11.1 Review *continued*

6 The spotted jelly (*Mastigias papua*) needs to incorporate free-living algae called zooxanthellae, because it obtains its energy mainly from the carbon fixed by the algae. The spotted jelly is also able to obtain energy by feeding on phytoplankton, tiny invertebrates and microbes. What type of interspecific relationship do the spotted jelly and algae have?

A predatory
B commensalism
C obligate mutualism
D facultative mutualism

7 What kind of organism is always the first link in a food chain? Explain why.

8 What is the best description for the role of each organism in the following food chain?



11.2 Ecological niches

The ecological niche of a species includes all its interactions with biotic and abiotic factors in the ecosystem. This includes the resources it needs for food and shelter, as well as its ability to survive and reproduce. It includes both how a population responds to factors (e.g. plants growing when resources are abundant) and how the species affects those factors (e.g. the resources depleting through plant uptake of nutrients).

FIGURE 11.2.1 Eucalypt trees interact with many biotic and abiotic factors in their ecological niche.

ECOSYSTEM ROLES

An organism's **ecological niche** is its role in its environment. This includes how the organism uses its resources and interacts with other species and its environment. It is essentially the organism's 'job description' in the ecosystem. For example, the ecological niche of a eucalypt tree in an open woodland ecosystem (Figure 11.2.1) would be:

- photosynthesis
- producing oxygen by photosynthesising
- absorbing water and nutrients from the soil
- providing shelter and food for organisms including plants, animals and fungi
- stabilising the soil.

COMPETITIVE EXCLUSION

The **competitive exclusion principle** is an ecological principle which states that two species cannot have the same niche in an ecosystem. This means that two species cannot use the same resource in the same space at the same time. If two competitors try to occupy the same ecological niche, one species will eliminate the other. This may occur through one species becoming extinct, or a species adapting to fill a different ecological niche (this can include moving to a different space, occupying the habitat at a different time, or changing its diet).

However, it is common for different species to use different parts of a resource at the same time, a term called resource partitioning. For example, brown creepers (*Certhia americana*) feed on insects on the trunk of a tree, while nuthatches (*Sitta* sp.) feed on insects among the branches at the top of a tree (Figure 11.2.2).

FIGURE 11.2.2 (a) Nuthatches (*Sitta* sp.) feed on insects in the canopy of trees, while (b) brown creepers (*Certhia americana*) feed on insects on the trunk.

BIOFILE S

The habitat and niche of small crabs

Small crabs survive in rock pools (their habitat) because they can shelter under seaweed or between rocks (microhabitats) and easily pick up food with their pincers (Figure 11.2.3). They feed on organic litter, a particular resource of rock pools (their niche). One example of the competitive exclusion principle is illustrated here where it is commonplace for only one species of crab to occupy this rock pool habitat niche.

FIGURE 11.2.3 This small hermit crab's ecological niche includes feeding on organic litter in a rock pool.

Many endangered species become threatened because they are unable to adapt to different ecological niches when competition arises. For example, the Australian koala (*Phascolarctos cinereus*) will only eat foliage from a few of more than 600 species of *Eucalyptus* tree that grow in Australia (Figure 11.2.4). Further, koalas are locally specific in their diet; for example, koalas in New South Wales forage on different eucalypts than those in Victoria. An ecosystem can only support a limited number of koalas due to their specific dietary preferences; therefore, when an ecosystem becomes unbalanced, the species comes under threat. This can be seen where eucalypt forests are being cleared by humans for development, leaving ecosystems with fewer eucalypt trees for koalas. The koalas then eat more foliage than the trees can regrow and the tree and/or koalas perish.

WS 4.4

FIGURE 11.2.4 The koala's ecological niche includes a locally specific diet, placing them at risk when changes to the environment occur.

BIOLOGY IN ACTION S

Adaptation of tigers

In 2012, ecologists studied the competition in Nepal's Chitwan National Park between humans and the Bengal tiger species (*Panthera tigris tigris*) for space and resources (Figure 11.2.5). Humans in the park include local people foraging for food and wood, as well as tourists and park rangers who patrol the area against poachers. Tigers use the space for hunting medium- to large-sized ungulates (hooved animals), as well as reproduction and other behaviours. The scientists discovered that both humans and tigers avoided each other, yet used the same space for activities. It was observed that in the national park, the usually day-active tigers had become active at night (Figure 11.2.6), when human activity was low. This is a response known as **temporal partitioning**, that is, occupying a new time niche to avoid competition.

FIGURE 11.2.5 A biologist tracing wildlife footsteps in Nepal's Chitwan National Park

FIGURE 11.2.6 The Bengal tiger (*Panthera tigris tigris*) in Nepal's Chitwan National Park has changed to nocturnal behaviour to avoid competition with humans.

11.2 Review

SUMMARY

- An organism's ecological niche is its role in the environment, the resources it uses, and how it interacts with other species and its environment.
- The competitive exclusion principle states that two species cannot have the same ecological niche in an ecosystem.
- Resource partitioning involves different species using different parts of a resource at the same time.
- Many endangered species become threatened because they are unable to adapt to different ecological niches when competition arises.

KEY QUESTIONS

1. Explain the term 'ecological niche'.
2. If two competitors try to occupy the same ecological niche, what may happen to the unsuccessful competitor?
3. Two species of monkey feed on the same tree; one species feeds on the young upper leaves of the top canopy, while the other species favours the large leaves of the lower limbs. What is this an example of?
4. Many endangered species become threatened when competition arises and they cannot adapt to new ecological niches. Provide an example of one such species.
5. Provide an example of how a species has moved to a different ecological niche when faced with competition.

11.3 Predicting and measuring population dynamics

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Chapter 7 explored the potential for exponential growth in populations (i.e. the birth rate of a population is higher than the death rate, allowing the population to grow), but many factors can affect population size and density and prevent initial or continued exponential population growth. The size of a population is affected by many factors interacting in complex ways. However, the effects of one factor can often amplify (increase) the effects of other factors.

ENVIRONMENTAL RESISTANCE

Environmental resistance is the term used to describe the sum of the factors that limit the growth of populations. Environmental resistance includes abiotic factors such as temperature, drought and fire, as well as biotic factors such as competition, predation and disease. These factors can reduce the health, reproduction rate and survival of individuals, leading to a reduction in the rate of population growth. Factors that influence population size in an ecosystem are either **density-independent factors** or **density-dependent factors**.

DENSITY-INDEPENDENT FACTORS

Density-independent factors affect a population's size regardless of the size or density of the population. They include:

- the conditions in which the species can survive; that is, its daily and seasonal **tolerance range** for various abiotic factors
- major changes or disturbances to the environment, such as bushfires, droughts or floods.

Tolerance range of a species to abiotic factors

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As discussed in Chapter 7, tolerance is an organism's ability to survive within the physical conditions of a location. For any one factor, such as temperature or light, there are limits that the organism can tolerate while maintaining homeostasis (internal balance). These limits are known as the organism's range of tolerance and are determined by the **genotype** (genes) and **phenotype** (observable traits), which allow the organism to adapt to its environment. Within these limits, organisms have what is known as an **optimum range** where they are best-suited to conditions and able to outcompete other species. A **suboptimum range** for an organism is the range of conditions in which it can survive, but it may be outcompeted by species that are better adapted to these conditions.

When graphed, an organism's tolerance to an abiotic factor is often a bell-shaped curve, as shown in Figure 11.3.1

Major changes to an environment

Other types of density-independent factors affecting population size are those related to sudden or major changes to an ecosystem. These can occur in a number of different ways, including:

- **natural disasters**, such as flood, bushfire (Figure 11.3.2a), drought, volcanic eruption, tsunami, earthquake and cyclone
- **anthropogenic changes** (human-made), such as construction or pollution.

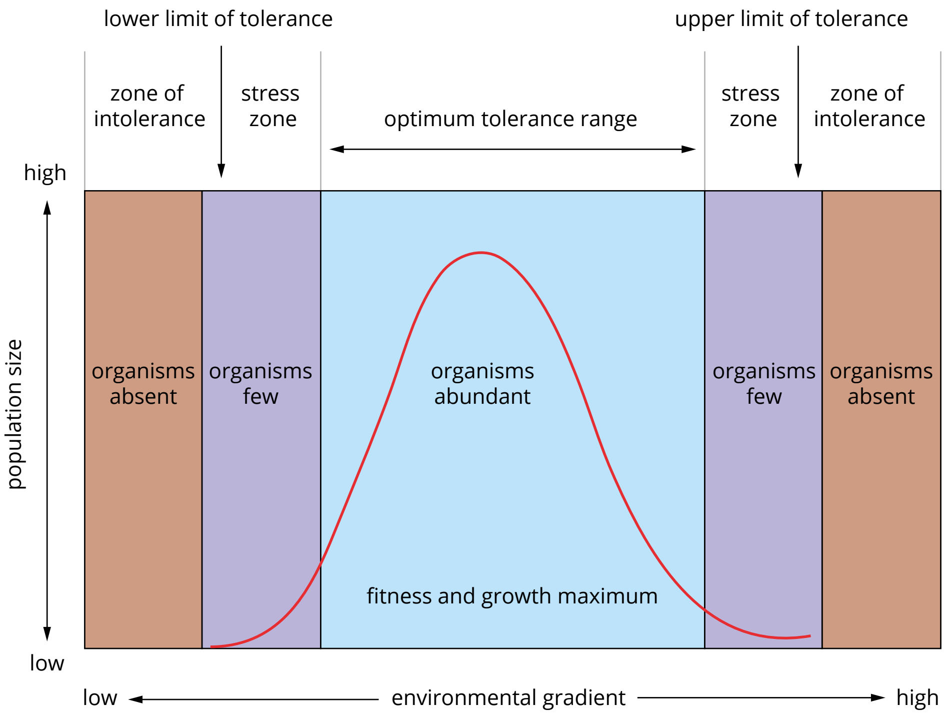


FIGURE 11.3.1 An organism's tolerance to an abiotic factor (e.g. temperature) is often a bell-shaped curve (indicated here with a red line). As the environmental gradient (change in abiotic factors) increases and decreases, fewer individuals are seen.

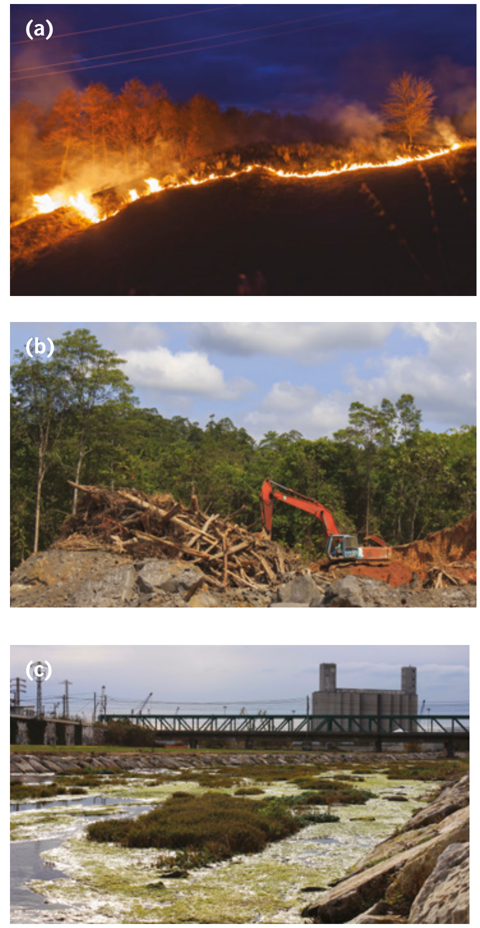


FIGURE 11.3.2 (a) Bushfires affect many animal and plant populations. (b) Clearing rainforests for oil palm plantations in Malaysia destroys habitat for many species, including elephants, tigers and orangutans. (c) Pollution of waterways reduces oxygen levels and causes the death of fish and other marine organisms.

Natural disasters and human-made changes can have wide-ranging effects on plant and animal species. The destruction of habitat (Figure 11.3.2b) can displace many organisms, and some major changes to the ecosystem can kill organisms (Figure 11.3.2c).

DENSITY-DEPENDENT FACTORS

Density-dependent factors influence the rate of births and deaths in a population. The effects of these factors increase as the population increases. Density-dependent factors include:

- competition for resources, such as food, water, shelter and mates
- predation
- crowding
- parasitism (a type of symbiosis)
- infectious disease.

Competition

All organisms have a set of biological requirements for their survival and reproduction. All organisms need resources such as nutrients and water to sustain themselves, shelter for protection, and mates for reproduction. If two organisms require the same resource and there is limited access to this resource, there will be competition. Competition can be intraspecific (between individuals of the same species) or interspecific (between different species).

Limiting factor

The **limiting factor** of a population's size, density or growth is the scarcest of the resources needed by a population. For example, food, water, shelter, nutrients and light are essential for a population's growth. If all of these resources except water are available in large quantities, water is the limiting factor and organisms will have to compete for it (Figure 11.3.3).

FIGURE 11.3.3 During a drought, water becomes the limiting factor for population growth.

BIOLOGY IN ACTION S

Competition and barnacle distribution

On rocky shores, different species of barnacles grow in different vertical zones (Figure 11.3.4a). For example, in Scotland, *Balanus* barnacles live on rocks below the average high tide mark. These barnacles are covered by water for some part of each day. *Chthamalus* barnacles live on the rocks in the splash zone, above the high tide mark and the *Balanus* barnacles.

There are two possible explanations for this zonation. These two species may be restricted in their distribution by their inability to survive in each other's zone (microhabitat) (Figure 11.3.4b). Alternatively, competition between the two barnacles may be limiting their distributions (Figure 11.3.4c).

To determine the cause of the zonation of the barnacles, researcher JH Connell designed an experiment. He first removed *Chthamalus* barnacles from rocks in the splash zone. He found that *Balanus* still would not move into the zone and live there. He concluded that this barnacle cannot tolerate the exposed conditions of the splash zone.

When Connell removed *Balanus* from underwater rocks, however, he found that *Chthamalus* did move down and survive below the water line. Thus competition is limiting the distribution of *Chthamalus*, restricting it to the harsher splash zone. Young *Balanus* barnacles grow more rapidly than young *Chthamalus* in the lower zone and vigorously grows over and crushes its competitor.

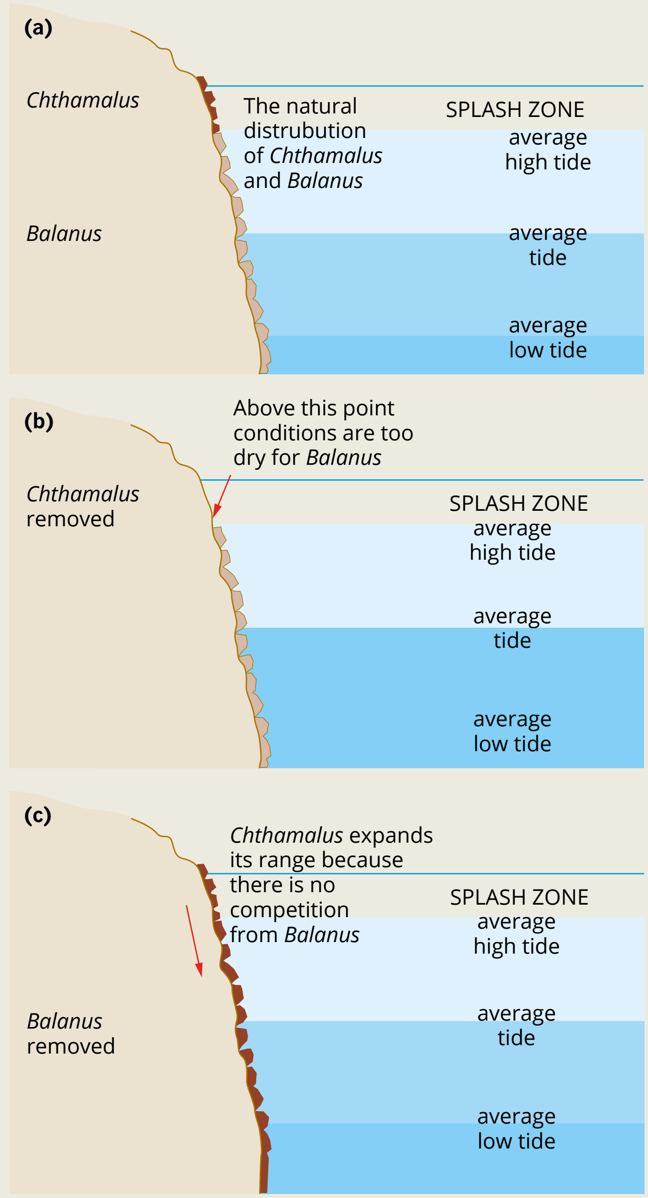


FIGURE 11.3.4 (a) The distribution of *Balanus* and *Chthamalus* barnacles on rocks on a Scottish shore is controlled by characteristics of the organisms and competition. (b) *Balanus* is restricted to deeper water because it is intolerant of the exposed conditions of the splash zone. (c) *Chthamalus* is restricted to the splash zone because it is outcompeted at lower depths by the stronger growing *Balanus*.

Interspecific and intraspecific competition

Competition can be interspecific or intraspecific. Interspecific competition occurs when different species compete for the same resource. For example, different species might need tree hollows for nesting and shelter. If trees with hollows are blown over or cut down, hollows might become the limiting factor for these species and they will have to compete for available sites (Figure 11.3.5). If one species is much more abundant or much stronger than the other, then the population of the weaker species will decline.

Intraspecific competition occurs when individuals of the same species compete for a resource. For example, if the food resource of a species suddenly becomes scarce, individuals of the same species will have to compete for the remaining food (Figure 11.3.6).

FIGURE 11.3.6 Capuchin monkeys live in a hierarchical group. These monkeys are territorial and the strongest individuals obtain much larger quantities of food than the rest and thus have a higher fitness. The weakest individuals die.

Competition can result in reduced growth, inability to reproduce and death or emigration. Either type of competition is more likely to occur when population densities are high and there is greater demand for resources. However, intraspecific competition is far more likely to occur than interspecific competition, because all individuals in a population have the same basic requirements for survival. Different species generally have different basic requirements for survival, although some of their needs might overlap.

Both kinds of competition select for stronger individuals or species. In intraspecific competition only the strongest individuals will be able to acquire the resources needed to survive. In interspecific competition, if one species is much more abundant or much stronger than the other, then the population of the weaker species may decline. An example of this is shown in Figure 11.3.7.

Predation

Another way in which a species can affect the population of another species is through a feeding relationship, such as predation. If the density of the prey species increases, predators will have more access to this source of food and their population will increase. This will then reduce the population of the prey species because more predators are eating them. As the number of prey falls, intraspecific competition in the predator population will reduce its population size.

Predator and prey relationships constantly fluctuate in this way. For example, the Canadian lynx (*Lynx canadensis*) preys almost exclusively on the snowshoe hare (*Lepus americanus*) (Figure 11.3.8). The population of hares varies according to factors such as climate, disease and availability of food.

FIGURE 11.3.5 The pink cockatoo (*Cacatua leadbeateri*), also called the Major Mitchell's cockatoo, needs tree hollows for nest sites and shelter. Other species in the ecosystem, such as parrots, owls, bees and possums, also compete for tree hollows.

FIGURE 11.3.7 Strawberry clover. When white clover and strawberry clover are planted together in the same field, the strawberry clover with its longer leaf stalks grows taller, towering above the shorter white clover. Strawberry clover competes better for space and shades the other species, eventually excluding it.

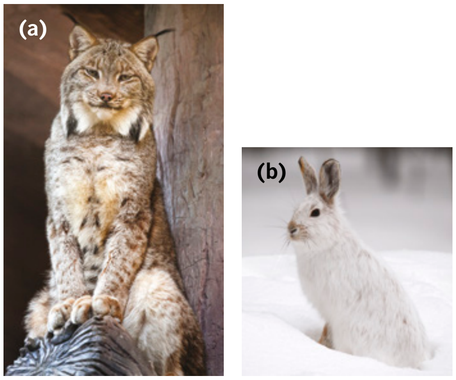


FIGURE 11.3.8 The (a) Canadian lynx (*Lynx canadensis*) and (b) snowshoe hare (*Lepus americanus*) form a predator–prey relationship.

An increase in the hare population leads to an increase in the lynx population. When there are more predators, the hare population may decline because more are killed by lynxes. This in turn may cause the lynx population to decline again. The graph in Figure 11.3.9 shows this repeating cycle.

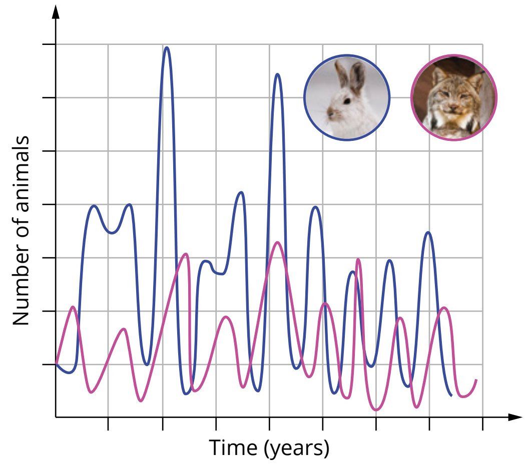


FIGURE 11.3.9 As the number of prey (snowshoe hares, indicated by the blue line) increase, so do the number of predators (Canadian lynxes, indicated by the pink line). Over time the prey population decreases as a result of predation, which leads to a decrease in the predator population.

Crowding

FIGURE 11.3.10 As population density increases, more aphid individuals develop wings.

Crowding affects populations of different species in different ways. For example, when the density of aphids is low few aphids develop wings, because they do not need to move far to obtain the resources they need. However, as the population density increases, more aphids develop wings (Figure 11.3.10). Winged aphids can only produce about half the usual number of offspring, but they can disperse to areas with more resources and form new populations.

Some animals become stressed when their density is high and may produce fewer offspring, or their immune systems become affected and they will be more prone to disease infection. The density at which negative effects occur is different for each species.

Parasitism

Parasitism, a type of symbiotic relationship, occurs when an organism lives in or on its host for an extended period of time or for its entire life cycle. When population density increases, individual organisms have more contact with each other. They are also more likely to be weakened; for example, as a result of limited supply of a resource such as food. By these means, parasites are more easily able to invade and spread in a host species of increased density.

FIGURE 11.3.11 Some species of *Anopheles* mosquitoes carry a parasite called *Plasmodium*, which causes malaria in humans and other animals. Most human deaths resulting from malaria occur in Africa, because the species of mosquito there has a long lifespan and a tendency to bite humans rather than other animals.

Infectious disease

Diseases may spread faster within a denser population, assuming that conditions are favourable for infection. Disease-causing fungi, bacteria and viruses that can kill individuals may then affect the size of the host population. However, organisms in natural environments may be infected with a disease but still be able to survive and reproduce.

A critical factor for any pathogen (disease-causing agent) is the method by which it spreads to other individuals (Figure 11.3.11). The rate at which a pathogen spreads depends on various factors, including environmental conditions such as wind, water flow and temperature. The genetic variation of the host population can limit the spread of a pathogen, because a more genetically diverse host population is more likely to have resistant individuals.

BIOLOGY IN ACTION CC S

A species facing the fight of its life

The Tasmanian devil is the world's largest surviving marsupial carnivore, and is found nowhere else on Earth. Tasmanian devils weigh up to 12 kg and live approximately 5–6 years in the wild; they inhabit open eucalypt forests, woodlands and coastal scrub where their prey of small marsupials, such as possums, are abundant. The Tasmanian devil is now under threat of extinction in the wild due to a contagious cancer known as devil facial tumour disease (DFTD). DFTD is characterised by the appearance of tumours on the face, mouth and neck which metastasise (spread to other parts of the body) and can cause death within months due to starvation or suffocation (Figure 11.3.12).

Current conservation efforts for the Endangered Tasmanian devil include the maintenance of a captive population of individuals—an 'insurance population'—which, if necessary, can return populations to the species' original home range if wild populations become extinct. In order for the captive breeding program to be successful, at least 95% of the wild genetic variation of the species must be maintained in the captive population. Biologists working in the captive breeding program use both studbooks and molecular biology tools to monitor genetic variation and ensure that captive parents and offspring have similar levels of genetic variation to the individuals in wild populations. Studbooks are records of an animal's breeding history and are used by biologists to match breeding pairs. Molecular tools are used to look at the genetic make-up of an individual, and provide a more accurate assessment of their ancestry.

FIGURE 11.3.12 Biologists take samples from a wild Tasmanian devil (*Sarcophilus harrisii*) to test for the presence of DFTD. (b) A Tasmanian devil with DFTD.

ECOSYSTEM CARRYING CAPACITY

In the absence of a limiting factor, the population growth of a species will always be exponential. However, in a real ecosystem, population growth is affected by density-dependent factors such as competition for resources.

When a species' population reaches **equilibrium** and becomes relatively constant, with the number of births and deaths in the population cancelling each other out, the species has reached the maximum population size that the ecosystem can sustain indefinitely. This is the ecosystem's **carrying capacity** for that species.

Equilibrium is a balance between opposing factors that keeps a parameter (such as population size) stable. For population size, these include the balance of births and deaths, immigration and emigration.

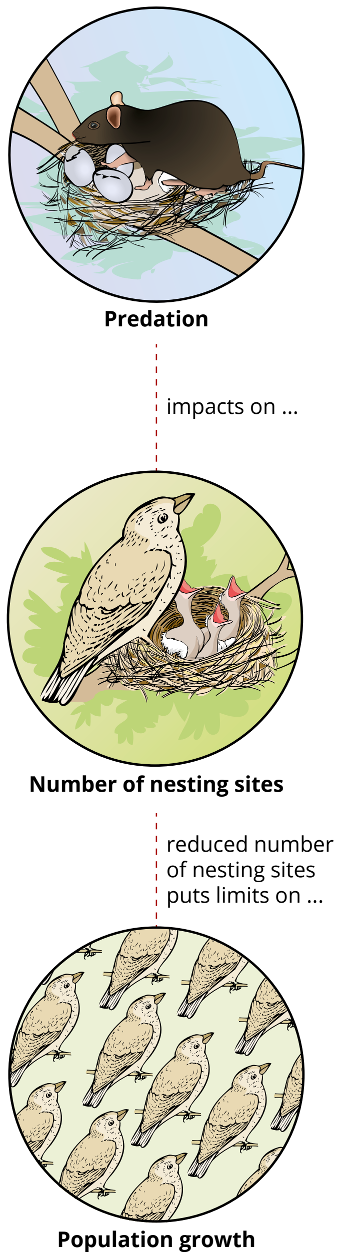


FIGURE 11.3.14 Birds that cannot find a nesting site or sufficient food to raise their young cannot reproduce, which affects population growth. Predation also limits the growth of a prey population.

The S-shaped graph in Figure 11.3.13 shows the initial exponential growth of a population, which then flattens out as it begins to be affected by density-dependent factors. The population growth rate may decline until birth and death balance each other and the population is limited to the carrying capacity of the environment. This pattern of growth is known as **logistic growth**.

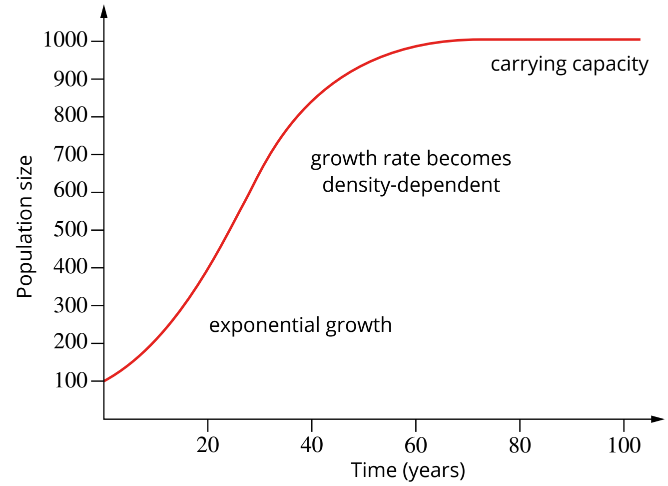


FIGURE 11.3.13 As a population increases, density-dependent factors, such as competition, may become important for limiting population growth.

Consider the following example. A new volcanic island emerged in the middle of an ocean and became populated with plants and insects. A few birds of one species happened to be carried to the island by strong winds. They raised young and fed on the seeds, insects and fruit available. As they were the only bird species, they had no competition for space or food and no natural enemies, so the population grew rapidly. Eventually there was no space left for new nests. Seeds, fruit and insects became scarcer, and then rats arrived on the island by ship and began eating bird eggs. The bird population then levelled out (Figure 11.3.14).

The graph in Figure 11.3.15 shows the changes in the size of the bird species population over time. This pattern of growth is observed in every population in a natural environment.

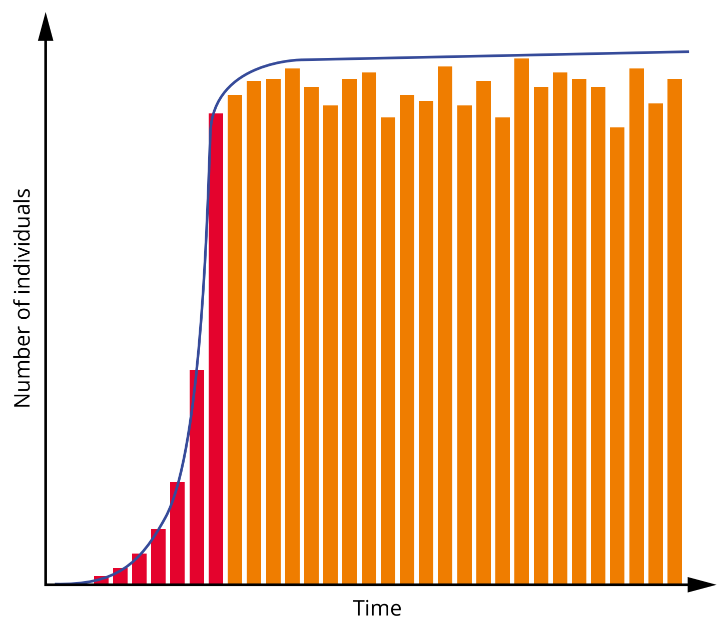


FIGURE 11.3.15 Initially the bird population grew increasingly quickly. When the population size reached the point where nesting areas and food were scarce, the population stabilised. The arrival of rats began a predator–prey relationship that caused the population to fluctuate.

The dynamic nature of carrying capacity

The carrying capacity of an environment is dynamic; that is, it varies over time. Factors that can affect carrying capacity include:

- weather and climate changes
- major changes in an ecosystem
- fluctuations in populations of food species or competitors.

The factors that can affect carrying capacity can be abiotic or biotic (Table 11.3.1). Water availability is an example of an abiotic factor that can affect carrying capacity. For example, during a drought water availability might become the limiting factor for a population of kangaroos, and the number of individuals that the environment can support will be reduced.

TABLE 11.3.1 Abiotic and biotic factors affecting carrying capacity

Abiotic	• soil • water • space • shelter
Biotic	• fluctuation of prey species • fluctuation of predator species • fluctuation of species which compete for resources

WS 4.5

BIOFILE S

Population crash

The reindeer (*Rangifer tarandus*) population of St Matthew Island in the Bering Sea is an example of a population that collapsed after exponential growth (Figure 11.3.16). During World War II the US Coast Guard introduced 29 reindeer to the island. The intention was to farm the reindeer for food, but this did not eventuate and the island was abandoned at the end of the war.

By 1957 the herd size had reached over 1000, thriving on the abundant lichens on the island. In 1963, 6000 reindeer were counted. However, the animals were by then showing signs of stress such as poor coat condition, and many were underweight. The lichen had almost disappeared, and the reindeer were feeding on less nutritious plants such as sedges. When observers returned in 1966, the island was scattered with reindeer skeletons. The herd numbered just 42, with no fertile males and no calves. The reindeer had exceeded the carrying capacity of the island, and the decline of the population had been rapid. By the 1980s there were no reindeer left on the island.

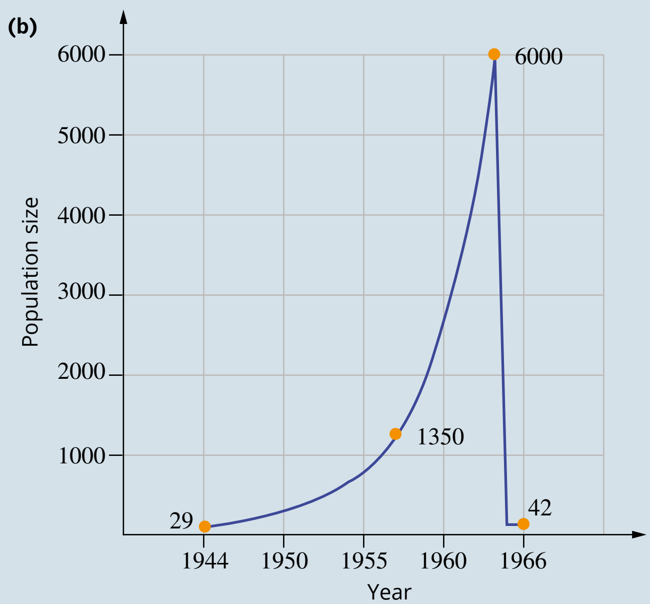


FIGURE 11.3.16 The initial population of reindeer (*Rangifer tarandus*) (a) on St Matthew Island after World War II grew from 29 individuals to 6000 in 19 years. (b) The population crashed after the carrying capacity was exceeded and the reindeer's food resource was exhausted. Eventually the reindeer disappeared from the island.

MEASURING POPULATIONS IN AN ECOSYSTEM

When studying ecosystems, it is often necessary to determine the type and number of populations and organisms living in an area. In natural environments, it is usually impossible to count all the individuals of a species. Even just counting the living things in your school would take a very long time. Sampling gives us a good idea of the organisms in an ecosystem without needing to count each one. Table 11.3.2 outlines some fieldwork techniques and when they are best used.

When sampling in the field, you should always consider the time and equipment available, the organisms involved and the impact the sampling may have on the environment.

TABLE 11.3.2 Summary table of common fieldwork techniques

Method	Procedure	Uses	Considerations
point sampling	Individual points are chosen on a map and the organisms at those points are counted.	determining the range of organisms that live in an area and how common they are	• time efficient • disturbance to the environment is minimised • rare organisms may be missed
transect sampling	Lines are drawn across a map. Organisms occurring along the line are sampled.	determining how the community changes in an area and how common organisms are	• time efficient • disturbance to the environment is minimised • rare organisms may be missed • only suitable for sampling stationary or slow-moving organisms
quadrat sampling	Sampling squares (quadrats) are placed in a grid pattern on the sample area and the occurrence of organisms in each quadrat is noted.	determining the range of organisms that live in an area and how common they are; this is a good way to obtain data over a large area	• time consuming to do well • only suits slow-moving or stationary organisms • disturbance to the environment is minimised
mark–recapture	Animals are captured, marked and then released. After a suitable time period, the population is resampled using the same method.	determining the total population of highly mobile species like birds or possums as the movements of individuals can be tracked	• time-consuming to do well • not suitable for slow-moving or stationary organisms • marking of animals should not affect their behaviour or movement

Point sampling

Point sampling involves counting organisms only at selected points (Figure 11.3.17). These points might be selected randomly or regularly, depending on the type of sampling being done. It can be used to determine the range of organisms that live in an area and how common they are. Point sampling is quick, but you might miss rare organisms.

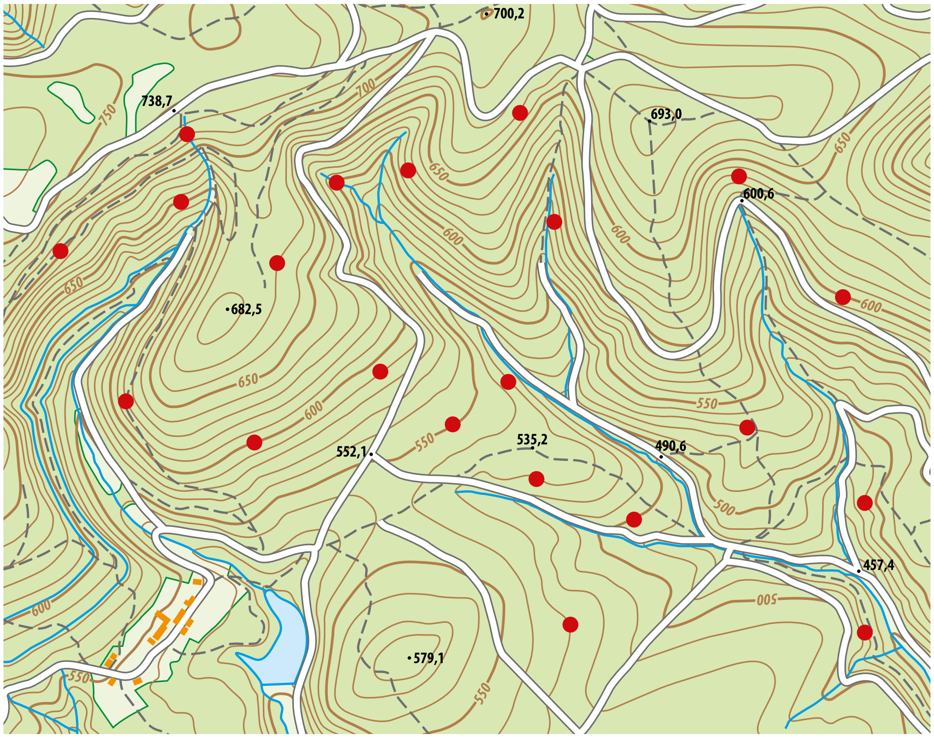


FIGURE 11.3.17 Randomly selected points for sampling marked on a topographical map. Sampling sites are indicated by the red dots.

Quadrats

A **quadrat** is a sampling method that allows you to estimate the number and variety of organisms in a large area by counting in a small area (Figure 11.3.18). A quadrat is usually square, and sometimes rectangular but may be circular. As suggested by its name, a quadrat was traditionally a square (a shape with four equal sides). A rectangle still conforms to the four-sided nature of the name. However, you may find it odd that a quadrat can also be a circle. The following points are helpful when planning to use quadrats.

- Quadrats are most useful in sampling immobile organisms such as plants or corals.
- Determine the size of the quadrat based on the size and abundance of the organism that you are sampling.
- The more quadrats you use, the more accurate your results will be.
- Very abundant organisms can be measured as a percentage of the area covered, rather than as a number of organisms.
- Photographing the quadrat can be a useful record-keeping method.

FIGURE 11.3.18 A botanist using a quadrat to monitor a threatened species of aquatic moss. The quadrat frame is a 50 cm square and is divided into twenty-five 10 cm squares. The presence or absence of the moss is recorded in each 10 cm square, over a large area marked out by string lines.

Transects

A **transect** is a straight line along which vegetation is sampled (Figure 11.3.19). Transects are useful for investigating the distribution of a population of plants, animals or insects across areas with different abiotic factors. For example, Figure 11.3.19 shows how a transect was used to sample and describe the change from eucalypt forest to heathland. A transect running from the sea to the land could be used to record the changes in species from rock pool ecosystems to mangroves to inland saltmarsh communities.

Physical aspects of the environment such as soil type and pH, salinity, amount of light, slope angle and height can also be measured along a transect to see if they correlate with changes in biological communities.

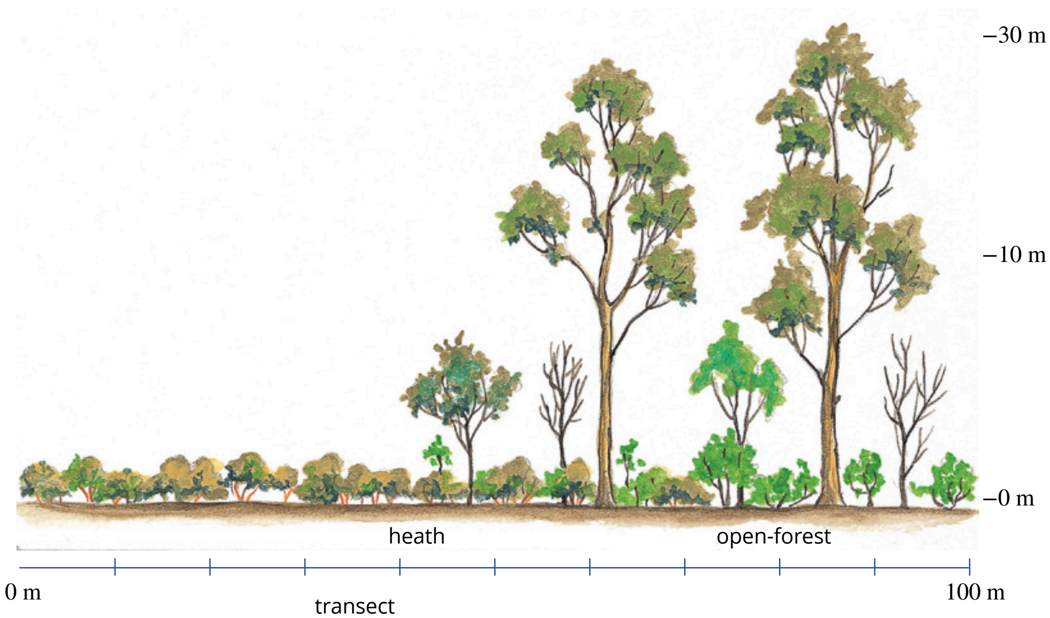


FIGURE 11.3.19 A transect is a straight line along which vegetation is sampled.

Techniques for sampling aquatic habitats

Marine and freshwater habitats can be sampled in many ways. Open water habitats are sampled by pulling a net through the water to collect swimming and floating organisms. Reefs and other underwater habitats are sampled using techniques similar to those used on land, such as quadrats and transects.

You might sample a freshwater habitat during your studies (Figure 11.3.20). Water is collected in a bucket and tipped into a white tray so that free-floating organisms can be easily spotted. Loose rocks are also collected to search for organisms that cling to them, such as stoneflies. Mud might also be collected and sampled to search for organisms such as nematodes and snails. Larger animals such as fish and yabbies can be collected using a net, then quickly identified and returned to the water.

FIGURE 11.3.20 Sampling organisms in a freshwater stream. The researchers have placed a sample of water and rocks in a white tray and are searching for different types of organisms. After sampling, the water and rocks are returned to the stream.

Mark–recapture

In a **mark–recapture** study, animals are captured, marked and then released. When they are recaptured or observed again, their mark is used to identify them (Figure 11.3.21). Mark–recapture is used to determine the total population of a mobile species such as birds and turtles. It can also be used to track the movements of individual animals. However, it is very time consuming and requires a lot of expertise to be done properly.

PA 4.1 PA 4.2 PA 4.3 PA 4.3

FIGURE 11.3.21 Bird banding is a common mark–recapture technique. The leg bands on these pied currawongs (*Strepera graculina*) uniquely identify each individual, and include information about where and when the birds were captured.

BIOLOGY IN ACTION CC S

Catching a grey nurse shark

The grey nurse shark (*Carcharias taurus*) has only two known populations remaining in Australian waters—one along the east coast of Australia, and one on the south-west coast of Western Australia. The species is under threat from human activities such as commercial and recreational fishing and shark control measures (beach nets and drum lines). The grey nurse shark has been listed as Critically Endangered, with past studies estimating between 1146 and 1662 adult individuals remaining. One important method for estimating the grey nurse shark population size is mark–recapture (Figure 11.3.22). The mark–recapture method is used to monitor the populations while ecosystem conservation methods are also implemented. Conservation measures include the establishment of marine parks near shark breeding waters and the implementation of sustainable fishing practices.

FIGURE 11.3.22 Researchers tagging a grey nurse shark (*Carcharias taurus*)

11.3 Review

SUMMARY

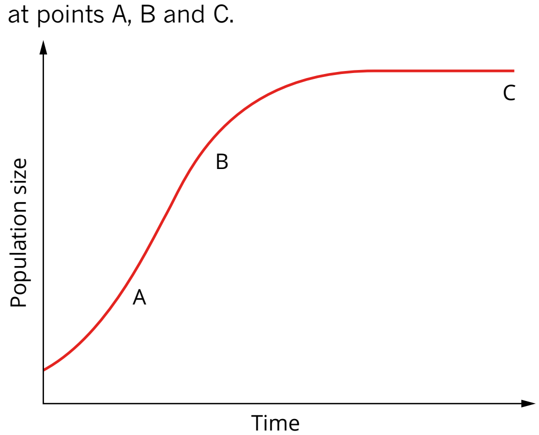
- Density-independent factors that influence population size and density include:
  - the tolerance range of a species to abiotic factors
  - major changes to an environment or chance disturbances.
- Density-dependent factors that influence population size and density include:
  - competition for resources
  - predation
  - crowding
  - parasitism
  - infectious disease.
- The limiting factor of a population's size, density or growth is defined as the scarcest of the necessary resources needed by a population to grow.
- Tolerance is an organism's ability to survive within the physical conditions of a location. Each organism has a range of tolerance determined by genotypic and phenotypic characteristics.
- Carrying capacity is the maximum population size of a species that its environment can sustain indefinitely. Carrying capacity is not fixed.
- Logistic growth is the pattern of growth that begins with exponential growth, and then flattens as density-dependent factors take effect, levelling out to carrying capacity. It is shown as an S-shaped curve on a graph.
- Field research techniques include:
  - point sampling, which involves choosing points on a map to count organisms
  - quadrats, a sampling method that allows you to estimate the number and range of organisms in a large area by counting in a small area; quadrats are usually square or rectangular
  - transects, where quadrats are placed at regular or random intervals along a line or area, and are useful for investigating the distribution of organisms across different areas
  - mark–recapture, which involves capturing, marking and recapturing animals to determine the total population of a highly mobile species, as well as to track the movements of individuals.

KEY QUESTIONS

1 Which answer lists only density-independent factors?
A predation; water depth; availability of sunlight
B competition for food; loss of habitat; drought
C competition for water; bushfire; overcrowding
D temperature; pH of soil or water; salinity levels

2 **a** Compare interspecific and intraspecific competition and give an example of each.
b Name three limiting factors that affect population growth.

3 Name the parts of the following logistic growth graph, at points A, B and C.



4 What is the difference between a quadrat and a transect?

5 Why is it important for quadrats to be located randomly across the area being studied?

6 Describe a sampling technique that would be suitable for each of the following investigations:
a the changes in a coastal community over sand dunes
b the number of turtles in a pond population
c the number of clover plants in a lawn

11.4 Extinction

EXTINCTION EVENTS

Species that fail to adapt to environmental changes or to compete for limited resources can die out. This loss of a species or groups of species is called extinction.

Background extinctions

The average rate of natural loss of species is called the **background extinction**. Extinction can occur as a result of changes in the physical environment or changes in the ecological interactions between species, such as the arrival of a new predator or competitor. The average life of a species varies, depending on the type of organism, but is generally a few million years. Based on the fossil record, some marine animals appear to have existed for 5–10 million years, while mammals tend to last only 1 million years. The coelacanth (*Latimeria chalumnae*) is considered a living fossil because coelacanths as a group date back to the Devonian period of 400 million years ago (Figure 11.4.1).

FIGURE 11.4.1 The coelacanth (*Latimeria chalumnae*) inhabits steep rocky shores in the western Pacific and Indian Oceans, living at depths of 150–700 m. An adult coelacanth may reach a length of 2 m.

A species is declared Extinct if it has not been seen in the wild for 50 years, despite efforts to find it.

Mass extinctions

Throughout the fossil record, there is evidence of some significant mass extinction events. **Mass extinctions** are large-scale extinctions following disruptive changes to the global climate, or loss of sea or land due to the shifting of continents (plate tectonics). Whether these extinctions were caused by global warming or cooling, drowning with sea-level rise, asteroid impacts, volcanic eruptions or perhaps even disease, the aftermath of such large extinction events leads to changes in selection pressures that affect the number of surviving species.

Mass extinctions, like the one that wiped out most of the dinosaurs at the end of the Cretaceous period, led to many vacant ecological niches. Remaining species may have taken advantage of the sudden availability of resources and reduced competition or predation.

Five mass extinction events are evident from the fossil record, and in each more than 50% of hard-bodied marine species became extinct (Figure 11.4.2). For example, during the Permian period (299–251 million years ago), all of the continents came together and shallow continental seas were gradually lost. This large land mass (called Pangaea) caused reduced rainfall, temperature extremes, harsh conditions and the death of many species including the extinction of marine trilobites. The fossil evidence is particularly well documented as hard-bodied organisms fossilise well, and the environmental conditions of shallow seas are ideal for the fossilisation process.

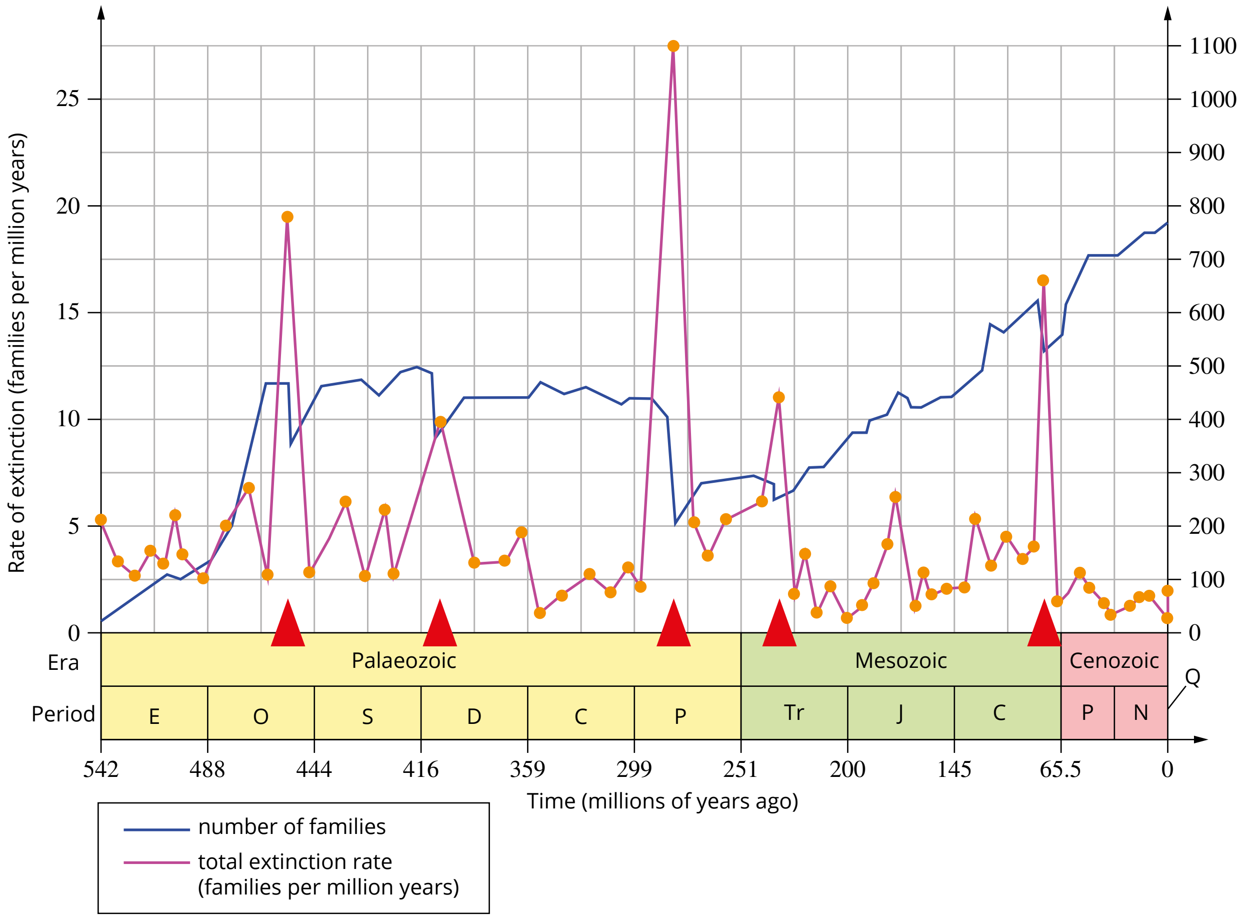


FIGURE 11.4.2 The five generally recognised mass extinction events, indicated by red arrowheads, represent peaks in the extinction rate of marine animal families (pink line and left vertical axis). These mass extinctions interrupted the overall increase in the number of marine animal families over time (blue line and right vertical axis).

RECENT EXTINCTION

Extinction events are not limited to the age of the dinosaurs. In recent times, humans have caused species extinctions at an accelerating rate. The rate and scale at which extinction is currently occurring has led many scientists to conclude that Earth's biodiversity is undergoing an extinction crisis—the sixth mass extinction event.

Extinctions have occurred for millennia as humans arrived on new islands and continents. A background extinction rate of 1–5 species per year was estimated for most of this time. However, the current background rate is estimated to be 1000–10 000 times that, meaning we are experiencing the greatest rate of species extinction since the dinosaurs were wiped out 65 million years ago. In the last 520 years, human activity has caused the extinction of 820 species; however, there is likely a large number of unknown species that have become extinct without documentation. For example, the San Cristóbal vermilion flycatcher (*Pyrocephalus dubius*) has recently been registered as a newly discovered species on the famous

Galápagos Islands. Unfortunately, there is one catch to the discovery—the species is already Extinct (Figure 11.4.3). Researchers studying bird specimens at the California Academy of Sciences recently distinguished the bird as a unique species (rather than a subspecies of other birds); however, it was discovered that the species likely became Extinct in 1987 when the last sighting was documented. The introduction of invasive rats on the island is the likely cause of the flycatcher's extinction, with the rats feeding on bird eggs.

Species are believed to be disappearing at 100 times the natural rate, with 99% of species threatened purely by human activities. The main causes of this human-driven species and biodiversity loss include: habitat alteration (including land clearing and habitat fragmentation from roads and urban areas), **invasive species**, pollution, hunting and wildlife trade (such as poaching). A fifth factor driving modern-day extinctions has also been added, with global climate change now listed as a major driving force for species loss.

The first species to become Extinct as a direct result of global climate change is the golden toad (*Incilius periglenes*) of Central America (Figure 11.4.4). This unique amphibian had many curious physical and behavioural features such as black and yellow poisonous skin and a lack of eardrums. Also, without the capacity to call to other frogs the golden toad would wave its arms to communicate. The last sighting of the species was in 1989 in the Costa Rican cloud forest of Monteverde, where a team of scientists removed a population of the species to an amphibian conservation centre. It is believed that global climate change affected the golden toad's specific habitat to such an extent that the species became susceptible to a range of other pressures, eventually leading to extinction. Global climate change caused the high-altitude rainforest habitat to become hotter and drier, leaving the toad vulnerable to a fatal skin disease known as chytrid fungus. This, combined with forest clearing and overcollection of species for wildlife trade, left the species vulnerable and unable to recover.

Due to the complexity of ecosystems, any extinction event will have 'knock-on' effects to biotic and abiotic factors in the species' environment. This means that a snowball effect occurs leading to damaged ecosystems, which are less resilient to further change. An example of this is the African teak tree (*Pericopsis elata*), which grows in the forests of Central and West Africa (Figure 11.4.5). Excessive logging of this species for furniture, boat and flooring trades have left the African teak tree endangered. Should this species become extinct, it would have devastating effects for the entire ecosystem, including soil stability, livelihoods of the local indigenous communities, as well as the survival of endangered species of chimpanzees, gorillas and elephants that inhabit the forests.

Extinctions in Australia

Australia has one of the highest rates of biodiversity loss in the world. The isolated ecosystems of Australia have seen the evolution of some of the world's most unique species. Many of Australia's species are found nowhere else, with 87% of mammal species, 93% of reptiles, and 45% of bird species endemic to the continent. The evolution of Australia's native species in isolation has left them vulnerable to change. When Europeans colonised Australia, their activities caused rapid alterations to ecosystems. In just over 200 years, dozens of Australian mammal, bird and plant species have become extinct and many more are threatened with extinction. The rapid extinction of species in Australia is due to a combination of factors including the introduction of invasive species, land clearance and alteration, habitat loss and altered fire regimes.

FIGURE 11.4.3 The San Cristobal vermilion flycatcher (*Pyrocephalus dubius*) of the Galápagos Islands was discovered as a new species after it had become extinct.

FIGURE 11.4.4 The golden toad (*Incilius periglenes*) of Central America is believed to be the first species to become Extinct as a result of human-driven climate change.

FIGURE 11.4.5 The Endangered African teak tree (*Pericopsis elata*), which if lost would have devastating effects on the ecosystem

BIOLOGY IN ACTION CC S

Saving the corroboree frog

Both the northern (*Pseudophryne pengilleyi*) and southern (*Pseudophryne corroboree*) corroboree frog species (Figure 11.4.6) are listed as Critically Endangered, being found only in small seasonal wetlands of the Australian Alps, in altitudes over 750 m. The tiny amphibian is only 2.5–3 cm in length with black and yellow colouring, and rather than jumping or leaping this frog 'walks'. The corroboree frog species is under threat from habitat degradation, drought periods and other climate changes, invasive weeds and pests, as well as disease caused by the chytrid fungus (*Batrachochytrium dendrobatidis*), which is now affecting amphibians globally.

Conservationists are working tirelessly to save the corroboree frog from the brink of extinction, with Australian biologists implementing a broad range of measures to give this species the best chance of survival. Conservation measures include the annual monitoring of populations, and captive breeding programs at zoos including Taronga Zoo and Healesville Sanctuary (Figure 11.4.7). Populations are already being returned to natural ecosystems, and scientists are researching the species and the threats facing it with the hopes of providing more information for targeted conservation measures.

FIGURE 11.4.6 The Critically Endangered southern corroboree frog (*Pseudophryne corroboree)* of the Australian alps is the subject of targeted conservation measures to avoid extinction.

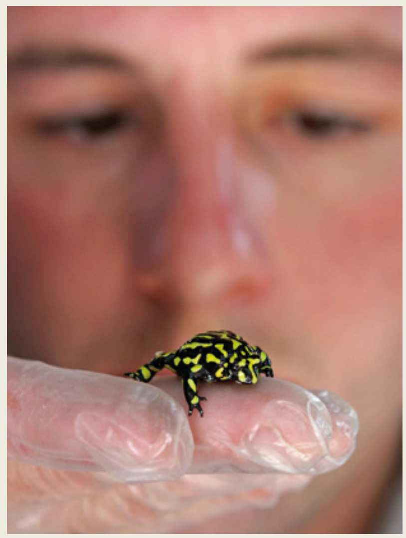


FIGURE 11.4.7 The corroboree frog is the subject of many research and breeding projects.

BIOFILE S

Tasmanian tiger left out in the cold

The Tasmanian tiger *(Thylacinus cynocephalus*), famous for its brown-grey striped fur and large, powerful jaws is a well-known example of recent extinction events. Once widespread on mainland Australia, and then confined to Tasmania, it is believed that the introduction of sheep for agriculture in the 1800s started the demise of the species. Rather than feeding on kangaroos and other prey, the Tasmanian tiger targeted the sheep as easy prey. As a result, a bounty was placed on their head by farmers trying to protect their flocks of sheep. Habitat destruction and disease further depleted populations and, once considered rare, zoos around the world began to take individuals or pairs as specimens. However, the Tasmanian tiger never survived long in captivity. The last known Tasmanian tiger (Figure 11.4.8) died at Hobart Zoo in 1936; as the story goes, the zoo keeper forgot to secure the individual in its enclosure on a particularly cold night and the last Thylacine died from exposure.

FIGURE 11.4.8 The last Tasmanian tiger *(Thylacinus cynocephalus*) in Hobart Zoo. The species became extinct in 1936.

11.4 Review

SUMMARY

- Species do not last forever but become extinct over time.
- Background extinction is the average rate of natural loss of species.
- Extinction can occur as a result of changes in the physical environment or changes in the interactions between species, such as the arrival of a new predator or competitor.
- Mass extinctions are large-scale extinctions following disruptive changes to global climates and land masses. Five mass extinctions are evident from the fossil record, and in each more than 50% of hard-bodied marine species became extinct.
- When a mass extinction occurs, remaining species may be able to take advantage of the changed environment and available resources. Over the course of many generations, natural selection will result in populations adapting to the various new environments, and new species evolve.
- In recent times, humans have caused an acceleration in species extinctions above the natural background rate.
- Many scientists agree that the sixth mass extinction is currently taking place, with the background extinction rate rising to 1000–10000 times the normal rate.
- Species are threatened globally by human activities including habitat alteration and pollution.
- Australia has a high species extinction rate, with the highest mammalian extinction rate of all countries on Earth.
- Due to ecosystem dynamics, any extinction event affects biotic and abiotic factors in the environment.

KEY QUESTIONS

1 What is species extinction?

2 What factors drive extinction?

3 **a** Define the term ‘mass extinction’.
b Explain how a mass extinction can result in new species evolving.

4 How do organisms fill ecological niches following mass extinction events?

5 Why is the estimate of extinct species numbers likely to be inaccurate?

6 List the major human impacts driving current global species loss.

7 Explain a recent extinction event.

Chapter review

11

KEY TERMS

abiotic
abundance
amensalism
anthropogenic change
autotroph
background extinction
biodiversity
biogeography
biotic
carnivore
carrying capacity
climate
climate zone
commensalism
community
competition
competitive exclusion
competitive exclusion principle
conservation
consumer
crowding
decomposer
density-dependent factor
density-independent factor
detritivore
detritus
disease
ecological niche
ecosystem
endemic
environmental resistance
equilibrium
extinction
facultative mutualism
facultative symbiosis
feeding interdependency
food chain
food web
genotype
geographic distribution
herbivore
heterotroph
host
interspecific
intraspecific
invasive species
life cycle
limiting factor
logistic growth
mark–recapture
mass extinction
mid-ocean ridge
mutualism
natural disaster
obligate mutualism
obligate symbiosis
optimum range
outcompetes
parasite
parasite–host food chain
parasitism
phenotype
point sampling
polar zone
predation
predator
predator–prey food chain
prey
primary productivity
producer
quadrat
resource partitioning
species
species richness
suboptimum range
symbiont
symbiosis
tectonic plate
temperate zone
temporal partitioning
threshold
tolerance range
transect
trophic level
tropical zone

REVIEW QUESTIONS

1 Define biodiversity.

2 Explain how ice ages can create new, and alter existing, climates.

3 Provide an example of plate tectonics creating a new ecosystem.

4 Using the terms ‘latitude’ and ‘climate’, explain why Antarctica has different abiotic conditions to Papua New Guinea.

5 Provide an example of a species’ behavioural response to climate.

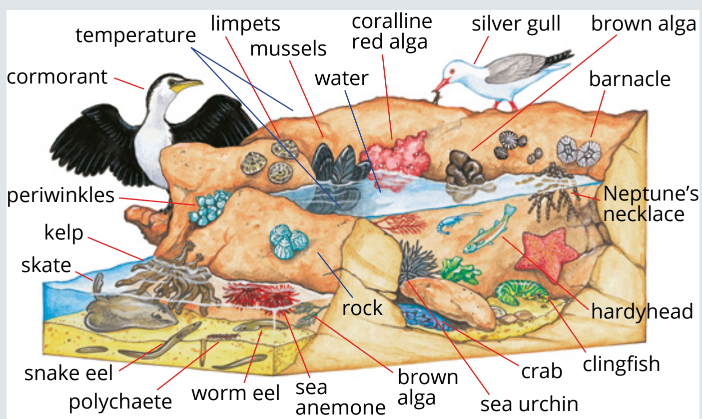
6 Which best describes the field of biogeography?

A the study of animal behaviour
B the study of land mass location
C the study of organism distribution
D the study of mammalian breeding

7 Explain why biodiversity is high in the tropics.

8 **a** Outline the difference between a food chain and a food web.
b Compare a complex food web with a simple one and explain which has an advantage over the other.

9 The diagram below shows the organisms in a rock pool environment.



a List the ways that the sea anemone might depend on the physical surroundings of the rock pool.
b Explain why the rock pool can also be considered part of a larger marine ecosystem.

10 **a** Define the term ‘food chain’.
b Arrange the following organisms in order from producer to highest-order consumer.
seabird, alga, small fish, human, zooplankton
c Explain how decomposers complete the cycle of matter in a food chain.

11 The following describes activity in an ecosystem's food web. Apply your knowledge of the physical environment to evaluate which abiotic factors are affecting organism activity.

'A white-bellied sea eagle is hunting for fish over the Pacific coast when it senses an incoming cold pressure front and accordingly changes its flight path to seek shelter over terrestrial environments. It spies a native mouse feeding on small native perennial grasses and swoops upon its prey. It takes its food back to its eyrie, located in a large eucalypt, to feed its hatchlings. The white-bellied sea eagle will remain with its young as night falls to protect them from predators such as the masked owl.'

12 On a seashore rock platform, a marine biologist notices bare patches in an area covered by sea lettuce (a seaweed). She covers some of these patches in fine mesh that allows light to penetrate and sea water to flow over it. The sea lettuce grows again where the mesh has been placed, but not in the other bare patches. How do you explain this? What relationship is occurring?

13 Apart from mutualism, what is another form of interspecific interaction in which an organism lives inside another organism? Give an example.

14 Most interactions are categorised by the effect they have on each of the species involved. Below is a list of interactions between organisms found in this chapter. For each interaction, state the type of interaction and whether there is no effect, a harmful effect or a beneficial effect on each organism. For example, European bream and tapeworm in its gut: parasitism, European bream (harmful effect), tapeworm (beneficial effect).

a desert quandong and an emu feeding on its fruit
b owl nesting in a tree hollow
c zooxanthellae and coral polyps
d cattle trampling on grass
e stick insect and a fungus growing on it
f lion feeding on an antelope

15 Describe an example of a benign relationship involving a tree and animal species.

16 **a** An epiphyte growing on a tree is an example of which kind of interaction? Explain your answer.
b If the tree becomes so laden with epiphytes that the branches could break, is this still the same kind of interaction? Explain your answer.

17 The flame robin builds its nest on a tree branch. What type or types of relationships could this be? Why?

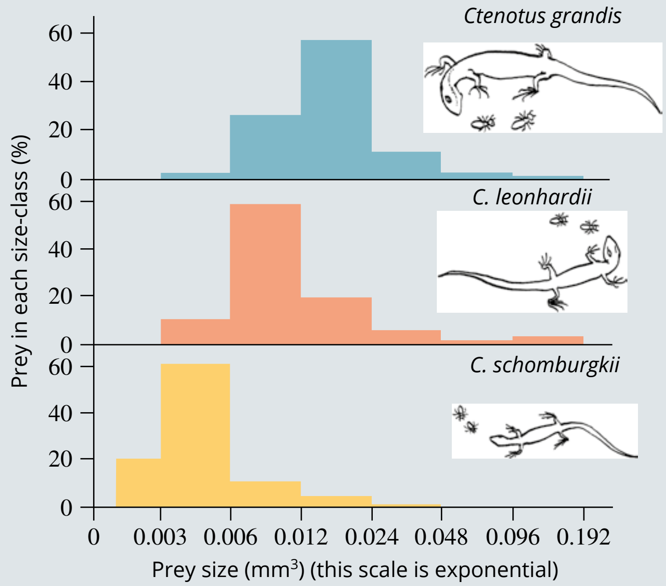
18 Explain how parasitism differs from mutualism. Give one example each of parasitism and mutualism.

19 Define the term 'ecological niche'.

20 Explain the competitive exclusion principle and provide an example of how a species overcomes competition.

21 Zooxanthellae inhabit coral polyps in the shallow, warm waters of coral reef ecosystems. Does the zooxanthellae's specific ecological niche make them more or less resilient to environmental change? Justify your answer.

22 The following graph gives information about three lizards and the termites that are their prey. Using the information in the graphs, explain how the three lizard species are able to exist together in an ecosystem.



23 A species of fish on a coral reef undergoes a rapid decline in population growth after the arrival of another species of fish that uses the same food resources. What kind of competition is this? Why would the population growth of the first fish decline?

24 Explain how quadrats can be used to determine the abundance of species in an ecosystem.

25 Which sampling method would scientists use to determine the distribution and abundance of the following species in an ecosystem?

a vegetation in a dry sclerophyll forest
b limpets on a rock platform
c tigers in a National Park

26 Define background extinction and explain how this rate has changed in recent times.

27 What is a mass extinction?

28 Scientists believe that a sixth mass extinction is occurring. What is some evidence for this?

29 What are the main drivers of modern-day species loss?

A habitat destruction and pollution
B invasive species and global climate change
C wildlife trade/hunting
D all of the above

30 After completing the Biology Inquiry on page 492, reflect on the inquiry question: What effect can one species have on the other species in a community? Recall three types of interactions within and between species and assess the effects of each interaction for the species involved.

CHAPTER 12

Past ecosystems

This chapter examines ecosystem change and the evidence that helps us understand these changes over short and long periods of time. You will gain insight into past ecosystems through palaeontological and geological evidence such as the ancient art of Indigenous Australians, geological formations and ice core samples. Technologies that are used to analyse changes in ecosystems, including radiometric dating and gas analysis, will also be investigated. You will learn about the evolution of present-day organisms from organisms in the past and develop an understanding of the reasons for changes in past ecosystems and the organisms that inhabited them.

Content

INQUIRY QUESTION

How do selection pressures within an ecosystem influence evolutionary change?

By the end of this chapter you will be able to:

- analyse palaeontological and geological evidence that can be used to provide evidence for past changes in ecosystems, including but not limited to: CCT ICT
  - Aboriginal rock paintings AHC
  - rock structure and formation
  - ice core drilling
- investigate and analyse past and present technologies that have been used to determine evidence for past changes, for example: (ACSBL005)
  - radiometric dating
  - gas analysis
- analyse evidence that present-day organisms have evolved from organisms in the past by examining and interpreting a range of secondary sources to evaluate processes, claims and conclusions relating to the evolution of organisms in Australia, for example: (ACSBL005, ACSBL027) CCT ICT
  - small mammals
  - sclerophyll plants
- investigate the reasons for changes in past ecosystems, by:
  - interpreting a range of secondary sources to develop an understanding of the changes in biotic and abiotic factors over short and long periods of time (ACSBL025, ACSBL026) ICT
  - evaluating hypotheses that account for identified trends (ACSBL001) CCT

12.1 Ecosystem dynamics: changes and causes

BIOLOGY INQUIRY CCT ICT WE

Building an ecosystem

How do selection pressures within an ecosystem influence evolutionary change?

COLLECT THIS...

- large sheet of paper
- coloured pens, pencils or craft supplies
- tablet or computer to access the internet

DO THIS...

1 Split the class into four groups. You will work in these groups for the entire activity.

2 Each group is to choose one of the following ecosystems:
   a Australian desert
   b shallow coral reef
   c humid jungle
   d coastal Antarctica.

3 Research your chosen ecosystem and record:
   a two abiotic challenges
   b one primary producer (uses energy from the Sun)
   c two grazing species (feeds directly on primary producers)
   d two carnivorous species (feeds directly on grazers).

4 Build a concept map, showing the relationships between these components (3a–d) of the ecosystem. Start with the abiotic factors and work up to the predatory species.

5 Change one of the abiotic factors. How does the system respond?

6 Choose one of your organisms. In pairs, research its defensive and/or predatory adaptations.

7 Annotate your concept map with these adaptations.

RECORD THIS...

Describe the way that each component of the ecosystem influences evolution.

Present your ecosystem model as a concept map to the class.

REFLECT ON THIS...

How does one change in an abiotic factor affect the whole ecosystem?

Over time, how might one species cause evolutionary change in another species?

What will happen if a species cannot adapt to rapid change?

How do selection pressures within an ecosystem influence evolutionary change?

FIGURE 12.1.1 Rock pool, Murrays Beach, Jervis Bay, New South Wales. Rock pools can be rich and dynamic ecosystems, inhabited by a diverse range of species that change with the tide.

GO TO ➤ Section 7.2 page 318

In Chapter 7 you learnt that an **ecosystem** is a biological system of interacting organisms and their physical environment. Every component of an ecosystem, living (biotic) and non-living (abiotic), plays a role in the processes that occur within the ecosystem. Think of a rock pool, which is home to small fish, crustaceans, molluscs and seaweeds (Figure 12.1.1). These creatures provide shelter or food for each

other and are all affected by abiotic factors of changing tides, wave action, wind and sunlight. We can examine ecosystems at any size and scale, from a small rock pool on the shore of a Sydney beach to the Middleton Reef ecosystem in the Tasman Sea. We can even study some of the largest ecosystems on Earth, formed by the currents of the Pacific Ocean.

The complexity of ecosystems and the many interactions between the organisms within them make ecosystems dynamic and ever-changing. A shift in one component can have a ripple effect on many components and potentially lead to changes to the whole ecosystem. We can observe these ecosystems as they are today, and technology allows us to understand how these systems have changed over time and how they may have looked in the past.

In this chapter you will learn about past ecosystems and how these complex dynamic systems and the organisms that inhabit them can change over time.

Ecosystems are complex and dynamic systems that change over time.

ECOSYSTEM STABILITY AND DISTURBANCE

Ecosystems are dynamic and changes are occurring all the time. Fluctuations in population numbers of a particular species or group of species can cause imbalance in an ecosystem. Ecosystem imbalance can be seen in the destruction and loss of **biodiversity** caused by **invasive species** (Figure 12.1.2). In a stable ecosystem, small changes are balanced out with no major effect on ecosystem processes or the structure. Stable ecosystems generally have higher biodiversity than unstable ecosystems.

FIGURE 12.1.2 Wild rabbits have become an invasive species in Australia since their introduction from England in 1788. Their population explosion has caused substantial damage to crops and Australia's native flora and fauna. Invasive species often cause loss of biodiversity and ecosystem imbalance.

Small changes in ecosystems are usually balanced out by interactions within the community.

Ecosystem imbalance occurs when disturbance is ongoing. This can create ecosystem instability.

Negative feedback loops

A stable ecosystem is a self-regulating system, where populations are maintained through a **negative feedback loop**. Feedback loops maintain balance in a system by increasing (**positive feedback loop**) or decreasing (negative feedback) a component in response to an imbalance in the system. For example, in a productive season with lots of sunshine and rain, plants are likely to thrive. The plants will grow and reproduce successfully leading to a spike in their population. An increase in the plant populations means there will be a lot of food available for herbivores. The number of herbivores is then likely to increase in response to the abundant food supply.

Birth rates may increase, survival rates will improve and animals may migrate to the areas with abundant food resources. If the number of herbivores becomes too high, the plants will be overgrazed and die out. This limits the food supply to the herbivores who will either move on to new habitats or starve. As the number of herbivores declines, the plants grow back and their population increases again (Figure 12.1.3). The overgrazing by the herbivores resulted in a negative feedback loop—the decrease in the food supply led to a decrease in the herbivores, which allowed the plant population to recover and the cycle to begin again.

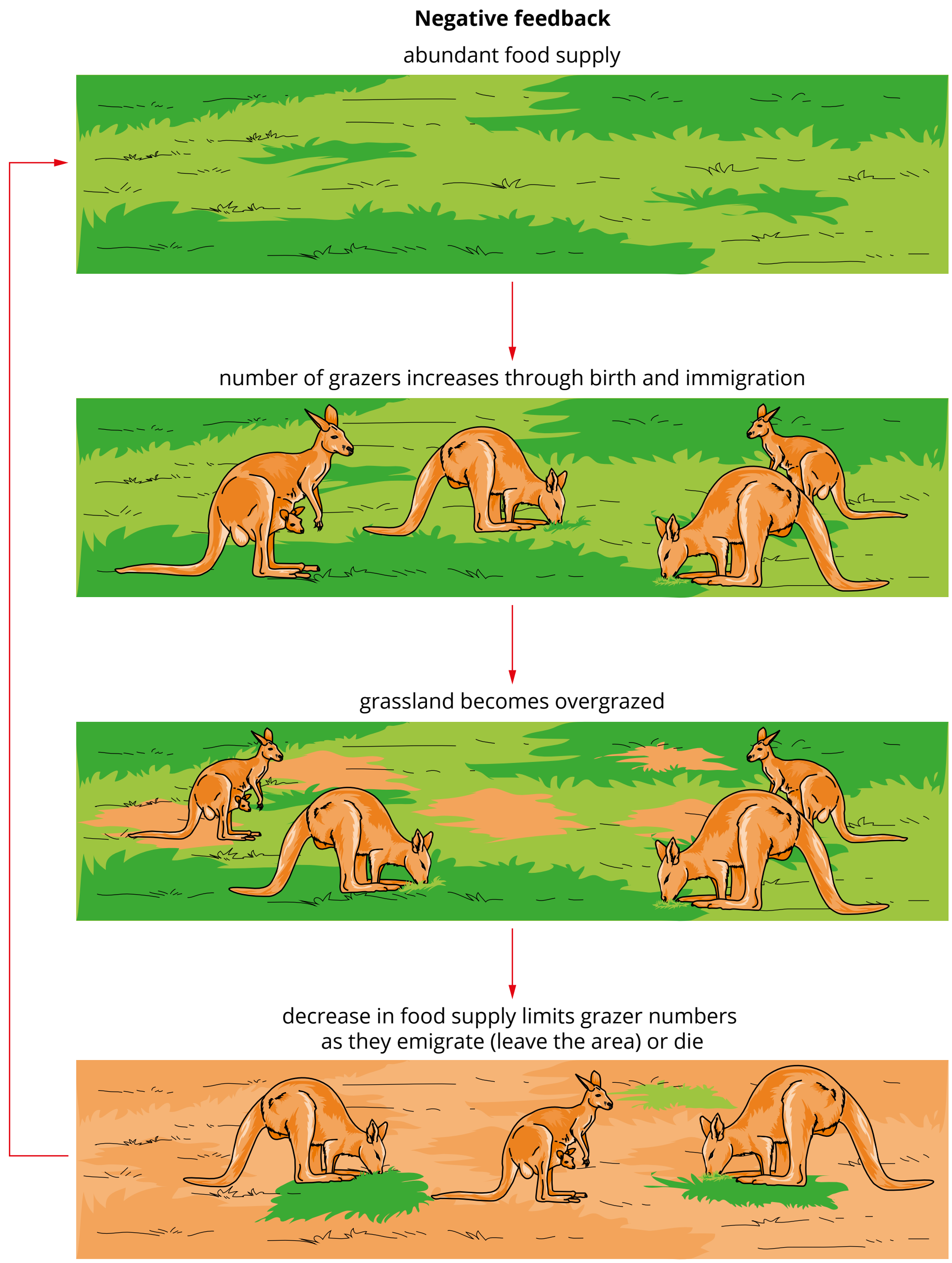


FIGURE 12.1.3 A negative feedback loop in a self-regulating grassland ecosystem. An increase in the plant population leads to an increase in the herbivore population. The large herbivore population overgrazes the plants, causing an imbalance in the ecosystem. The herbivore population declines in response to the reduced food supply, allowing the plant population to recover and the cycle to continue.

Feedback loops maintain balance in an ecosystem by increasing (positive feedback) or decreasing (negative feedback) a component in response to an imbalance in the system.

Disturbance

A stable ecosystem has the ability to self-regulate and maintain its average state even in the face of **disturbance**. A disturbance is an event that causes a temporary change in an ecosystem. Usually, the change is a loss of individual organisms, which may in turn alter the structure and function of an ecosystem. Ecological disturbances are natural events including earthquakes, floods, storms, volcanic activity, disease and fires. **Anthropogenic changes** or disturbances are human activities that can alter ecosystems, such as oil spills, forest clearing (Figure 12.1.4), pollution, radioactive contamination and introduction of invasive species.

An ecosystem can be described as **resistant** or **resilient**. A resistant ecosystem is tolerant to disturbances and remains fundamentally the same over a long period of time with little deviation from its average state. A resilient ecosystem can return to its normal structure and function after a disturbance.

The impact of a disturbance on an ecosystem depends on its intensity and frequency plus the spatial scale and distribution of the disturbance. For example, an extremely hot forest fire that reaches the canopy of a forest and burns for a long time will have a greater impact on an ecosystem than a short-lived, cooler burn through the undergrowth.

Though disturbances are destructive, they also provide opportunities. When some individuals are removed from an ecosystem, space is created for other organisms to reproduce and grow. Disturbances can encourage biodiversity in an ecosystem as different species move into an area or thrive in new conditions. Biodiversity can make an ecosystem more resilient and resistant as different species will respond to future disturbances in different ways.

FIGURE 12.1.4 Deforested habitat in Watagan State Forest, New South Wales. Deforestation is an example of ecosystem disturbance.

A resistant ecosystem can tolerate disturbances. A resilient ecosystem may change with disturbance, but can recover and return to its normal state after the disturbance.

Intermediate disturbance hypothesis

The **intermediate disturbance hypothesis (IDH)** proposes that high and low levels of disturbance reduce the species diversity of an ecosystem. Species diversity is maximised when disturbances are at an intermediate level.

Low-level disturbances are characterised by lower intensity or lower frequency where disturbances have little effect on an ecosystem and do not occur very often.

High-level disturbances are frequent and intense, occur often and have a great effect on ecosystem structure and function (Figure 12.1.5).

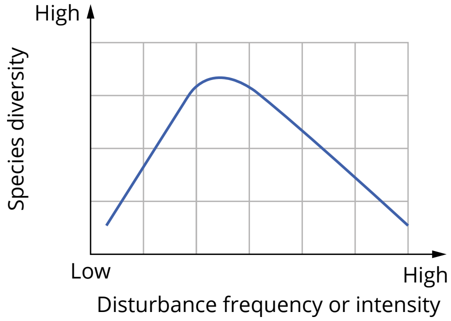


FIGURE 12.1.5 Graph showing the intermediate disturbance hypothesis

At high levels of disturbance, few species will be able to survive and levels of biodiversity will be low. At low levels of disturbance the most competitive species will eventually dominate an ecosystem, outcompeting other species and creating low levels of biodiversity.

Intermediate levels of disturbance allow for an increase in biodiversity over time and some competition until **competitive exclusion** occurs.

The intermediate disturbance hypothesis proposes that increases in biodiversity are greatest when there is an intermediate level of disturbance.

BIOLOGY IN ACTION CC S

Sea urchin barrens in south-east Australia

Sea urchin barrens are marine areas where destructive grazing by sea urchins has removed beds of kelp and seaweed. Kelp forest systems support a diverse range of species providing shelter and habitat for fish, corals, crustaceans, sea stars and sponges. Sea urchins also naturally occur in kelp forests, but if their population numbers are not regulated they can overgraze the kelp, destroying the habitat for other species.

Centrostephanus rodgersii (Figure 12.1.6a) is a large sea urchin native to New South Wales that has become an invasive species in south-eastern Australia. Urchin barrens are now becoming common place around the shores of Victoria and Tasmania where kelp forests once dominated (Figure 12.1.6b). Sea urchin populations are taking over these ecosystems for two reasons: changes to the East Australian Current (EAC) and the commercial fishing of southern rock lobsters (*Jasus edwarsii)*, their natural predators. The EAC is a body of warm, fast-moving water that flows from Australia to the west coast of South America. The movement of the EAC brings warm water and tropical marine life to subtropical regions of the south-eastern Australian coast. In recent decades, climate change has caused the EAC to move faster and push more warm water further south, carrying tropical species with it. Ocean temperatures in south-eastern Australia are now warm enough to allow the larvae of *C. rodgersii* to grow and reproduce as far south as Tasmania.

Rock lobsters are important predators of *C. rodgersii* and would normally be capable of regulating the populations of the invasive urchin. However, rock lobsters are commercially fished meaning their population numbers are limited and their predation on invasive sea urchins is not sufficient to keep the urchin population in check. Rock lobster populations are not overexploited to the point where their population numbers are at risk, but selection pressure on their population has caused a loss in ecosystem function.

This is an example of high levels of disturbance that are lowering the diversity of an ecosystem. The sea urchin invasion and the removal of rock lobsters from the ecosystem may not have the same effect if they were acting alone, but together they have a greater effect on biodiversity and ecosystem structure and function. The abiotic disturbance of warming oceans creates a biotic disturbance, which allows *C. rodgersii* to expand its range. The anthropogenic (human-induced) disturbance of rock lobster exploitation then exacerbates the imbalance by removing the sea urchins' natural predator from the ecosystem.

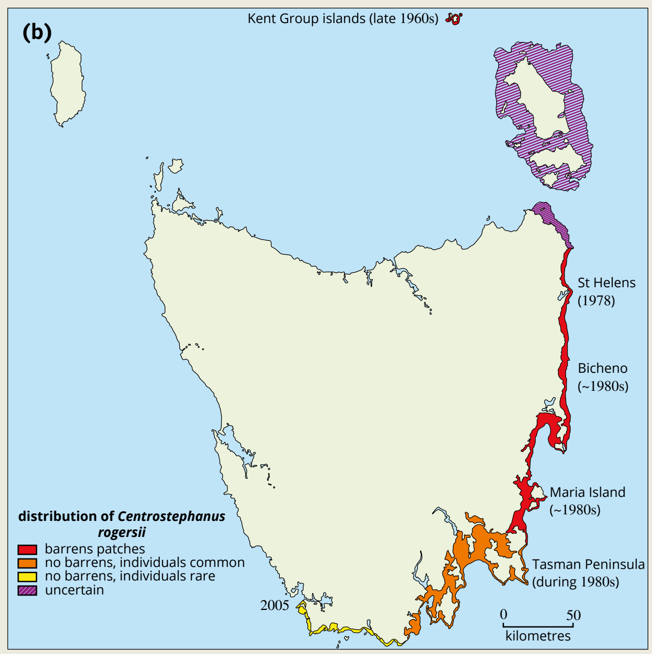


FIGURE 12.1.6 (a) The large sea urchin (*Centrostephanus rodgersii*) is native to the waters of New South Wales, but has become an invasive species in Tasmania where it destroys kelp forests, creating 'urchin barrens'. (b) The spread of *C. rodgersii* along the coast of Tasmania from the late 1960s to 2005. Areas where kelp forests have been replaced by urchin barrens are indicated in red.

BIOLOGY IN ACTION CC ICT S

Rock lobster army

Scientists working in St Helens, Tasmania have designed a management approach to control *C. rodgersii* numbers and prevent the spread of urchin barrens.

Underwater cameras confirmed that the main predator of the invasive sea urchins is the native southern rock lobster (*Jasus edwarsii*) (Figure 12.1.7) but only the largest lobsters are capable of overcoming the sea urchins' long spines. The research team decided to introduce an army of large rock lobsters to an urchin barren to see if the lobsters would stay in the area and control the invasive urchin population and give the kelp forests a chance to recover.

The large rock lobsters were fitted with radio transmitters and released into the urchin barren. Acoustic listening devices were attached to buoys within the area to transmit radio signals that allowed the scientists to locate the lobsters. They found that some lobsters moved on to less degraded habitat, but a large number still remained in the urchin barrens.

To check that the rock lobsters were actually feeding on the invasive urchins, the scientists located the lobsters and extracted faecal samples. Using DNA analysis they were able to identify prey species from the faecal matter. The DNA results showed that the invasive sea urchins were being consumed by the rock lobster.

The introduction of large lobsters reduced sea urchin numbers and had a significant impact on small, emerging urchin barrens. Small urchin barrens declined rapidly in size and seaweeds were able to regrow. The lobsters reduced urchin population numbers in large established barrens, but the sites where the large barrens had been showed no significant sign of seaweed recovery.

FIGURE 12.1.7 Southern rock lobster (*Jasus edwarsii*), native to the coastal waters of southern Australia, is a carnivorous predator that feeds on the large invasive sea urchin (*Centrostephanus rodgersii*).

TRENDS AND PAST CHANGES: THE GREAT BARRIER REEF ECOSYSTEM CASE STUDY

Coral reefs are complex, diverse marine ecosystems that support a wide variety of habitats, processes and species. The reefs are built by colonies of coral polyps, which are small, soft-bodied animals that are related to sea jellies and sea anemones. Coral polyps secrete calcium carbonate to form a hard, protective base. It is these calcium carbonate secretions that form the structure of coral reefs.

The Great Barrier Reef is the largest coral reef system in the world (Figure 12.1.8). It stretches over 2300 km along the coast of Queensland and covers approximately 344 400 km^2. It is so large that it can be seen from outer space. The Great Barrier Reef is made up of 2900 individual reefs and 900 islands and is home to many threatened species, some of which are only found in the Great Barrier Reef area. The Great Barrier Reef was classified as a World Heritage Site in 1981 and is considered one of the seven natural wonders of the world.

FIGURE 12.1.8 The Great Barrier Reef stretches over 2300 km along the coast of Queensland. It is the largest coral ecosystem in the world and is home to many rare and threatened species. Because of the Great Barrier Reef's unique biodiversity and ecological significance, the site has been listed as a United Nations (UNESCO) World Heritage Site.

Threats to the Great Barrier Reef

The greatest threat to the Great Barrier Reef is climate change, which is causing sea temperatures to rise, ocean acidification and increased extreme weather events.

Many reef species are sensitive to changes in sea temperature and pH levels. Corals may stop growing or die due to changes in these variables. Reduced coral growth and coral death has flow-on effects for other reef species that rely on corals for habitat.

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Rising sea temperatures

Reef-building corals are very sensitive to the effects of increasing sea temperatures. In Chapter 11 you learnt that many corals and anemones have a symbiotic relationship with tiny, photosynthetic algae called zooxanthellae. Zooxanthellae provide the corals and anemones with nutrients as well as their colour (Figure 12.1.9). Coral bleaching occurs from heat stress when water temperatures rise above normal levels and the zooxanthellae leave or are expelled from coral (Figure 12.1.10). The corals do not die from a bleaching event, but they will eventually starve if the zooxanthellae are not restored. Rising sea temperatures can reduce the stability of coral reef ecosystems if heat stress disturbance events occur often or over long periods of time. Consistently high water temperatures or many consecutive bleaching events can cause coral death and the destruction of reef ecosystems.

FIGURE 12.1.9 Colourful coral and sponges on the Great Barrier Reef. The bright colours of corals, sponges and anemones are due to their symbiotic relationship with photosynthetic algae.

Ocean acidification

Reef corals are negatively affected by ocean acidification in two major ways. First, acidic waters inhibit the corals' ability to make the calcium carbonate skeletons that give reefs their structure. The pH of ocean water decreases (becomes more acidic) when atmospheric levels of carbon dioxide (CO_2) are high and excess carbon dioxide is absorbed into the sea from the atmosphere. High levels of dissolved carbon dioxide in the ocean result in less free carbonate ions available for corals to create calcium carbonate structures. Acidic waters can also cause existing calcium carbonate reef structures (corals) to break down. In waters with pH levels that are lower than normal, calcium carbonate structures are dissolved faster than they can be replaced by corals leading to a net loss of important reef habitat for other species.

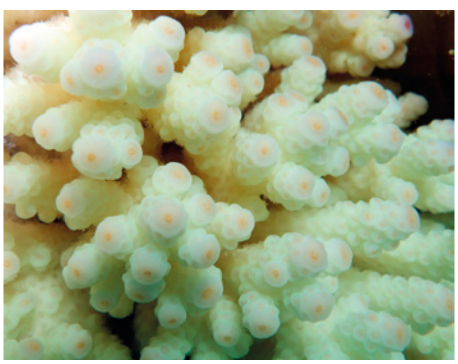

FIGURE 12.1.10 Coral in the early stages of bleaching. Coral bleaching is due to stress caused by rising sea temperature and acidity.

Extreme weather events

Extreme weather events such as cyclones and floods can cause long-term damage and fragmentation of reef systems (Figure 12.1.11). These weather events create strong wave actions that break the underlying reef structures (Figure 12.1.12). Turbulent waters can cause a change in water quality with decreased salinity and increased nutrient and sediment loads, which cause stress to many reef species. Coral reefs can withstand some weather disturbances, but may be unable to recover from frequent and intense weather events.

Two recent major tropical cyclone events, Cyclone Yasi (2011) and Cyclone Debbie (2017), have caused major structural and coral cover damage to the Great Barrier Reef. Since 2005 more strong cyclones (category 3 or higher) have been recorded than in previous decades.

Coral reefs usually take 10–15 years to recover after a major disturbance event. The back-to-back nature of recent disturbances has not allowed enough time for the Great Barrier Reef to be restored to its pre-disturbance state. Overall decline in coral cover can be attributed to a change in disturbance regime where intense disturbances are occurring frequently.

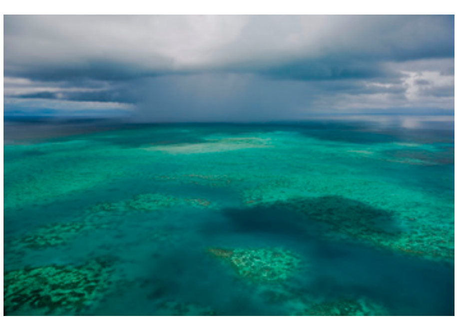

FIGURE 12.1.11 Storm clouds over the Great Barrier Reef, Queensland

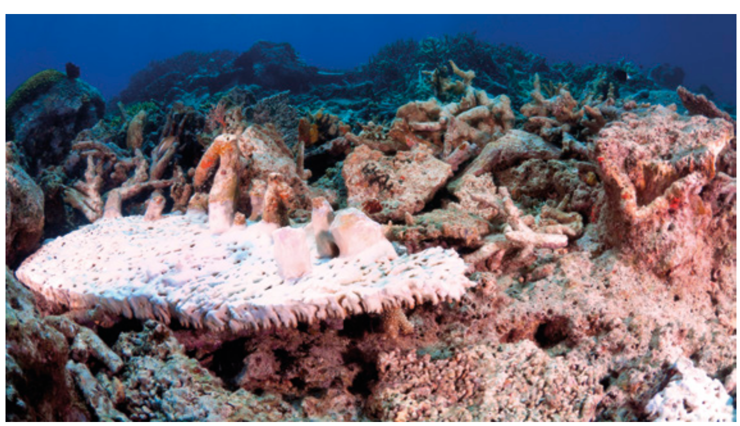

FIGURE 12.1.12 Broken and bleached coral after Cyclone Yasi in 2011, Great Barrier Reef, Port Douglas, Queensland

The Great Barrier Reef since the 1980s

A report released in 2012 stated that the coral cover of the Great Barrier Reef had reduced substantially since 1985 due to cyclones, coral bleaching and outbreaks of crown-of-thorns sea stars, which can destroy coral when in high numbers (Figure 12.1.13).

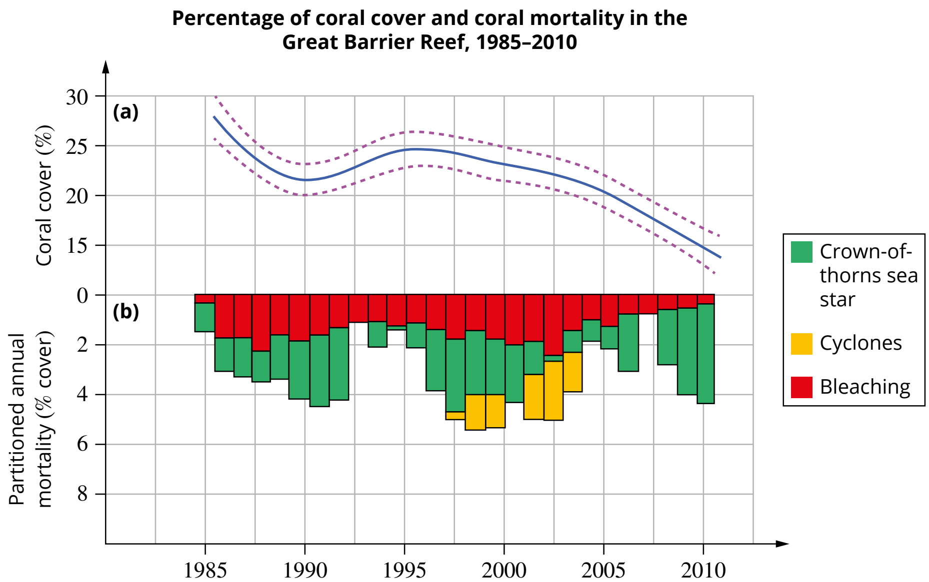

FIGURE 12.1.13 (a) Percentage of coral cover at 214 sites and (b) percentage of coral mortality (death) due to crown-of-thorns sea star invasions, cyclones and bleaching in the Great Barrier Reef between 1985 and 2010

During this time, sea surface temperatures in Australian waters had increasingly exceeded long-term sea temperature records. Extreme weather and coral bleaching events have continued to occur after this time.

Calcification (the production of calcium carbonate by corals) declined by 14.2% between 1990 and 2009. Ocean acidification had also occurred throughout this time, but is not the only factor contributing to the decline in coral calcification as other environmental changes, such as rising sea temperatures, occurred at the same time.

A study was conducted in the Great Barrier Reef to test the effect of ocean acidification on coral reef calcification. Researchers increased the pH (decreased acidity) of the water over an existing coral reef to mimic the estimated pH levels 200 years ago. Atmospheric carbon dioxide levels were much lower and oceans were less acidic 200 years ago. The study found that coral calcification was 7% higher in the reef in less acidic water (as it was 200 years ago) than in a reef in present-day conditions.

A survey conducted in 2016 found that corals in the north and far north region of the Great Barrier Reef have undergone substantial decline, with losses of up to 67% (Figure 12.1.14). This represents one of the largest coral die-offs ever recorded for the Great Barrier Reef. Although this part of the reef may recover in 10–15 years' time, it is expected that more bleaching events in this time will slow the recovery. Two-thirds of the reef was found to have minor damage with signs of recovery in the southern region. Scientists think that the southern part of the reef may be protected from heat stress by cooler water from the Coral Sea.

Bleaching events

The following is a timeline of coral bleaching events:

- 1998—one of the hottest summers recorded for the 20th century. Moderate to high levels of bleaching occurred where 50% of coral reefs were bleached, but most recovered fully and 5% were damaged

- 2002—moderate to high levels of bleaching where 60% of reefs were affected and about 5% of reefs suffered high mortality
- 2005–06—a bleaching event occurred and was isolated to the southern regions of the Great Barrier Reef where mortality was close to 30%
- 2016—record-breaking temperatures were associated with a mass bleaching event in 2016 where an average 67% loss of coral cover was recorded in the northern third of the reef, 6% in the central region and 1% in the south
- 2017—further record-breaking temperatures led to a bleaching event that substantially impacted the central section of the Great Barrier Reef.

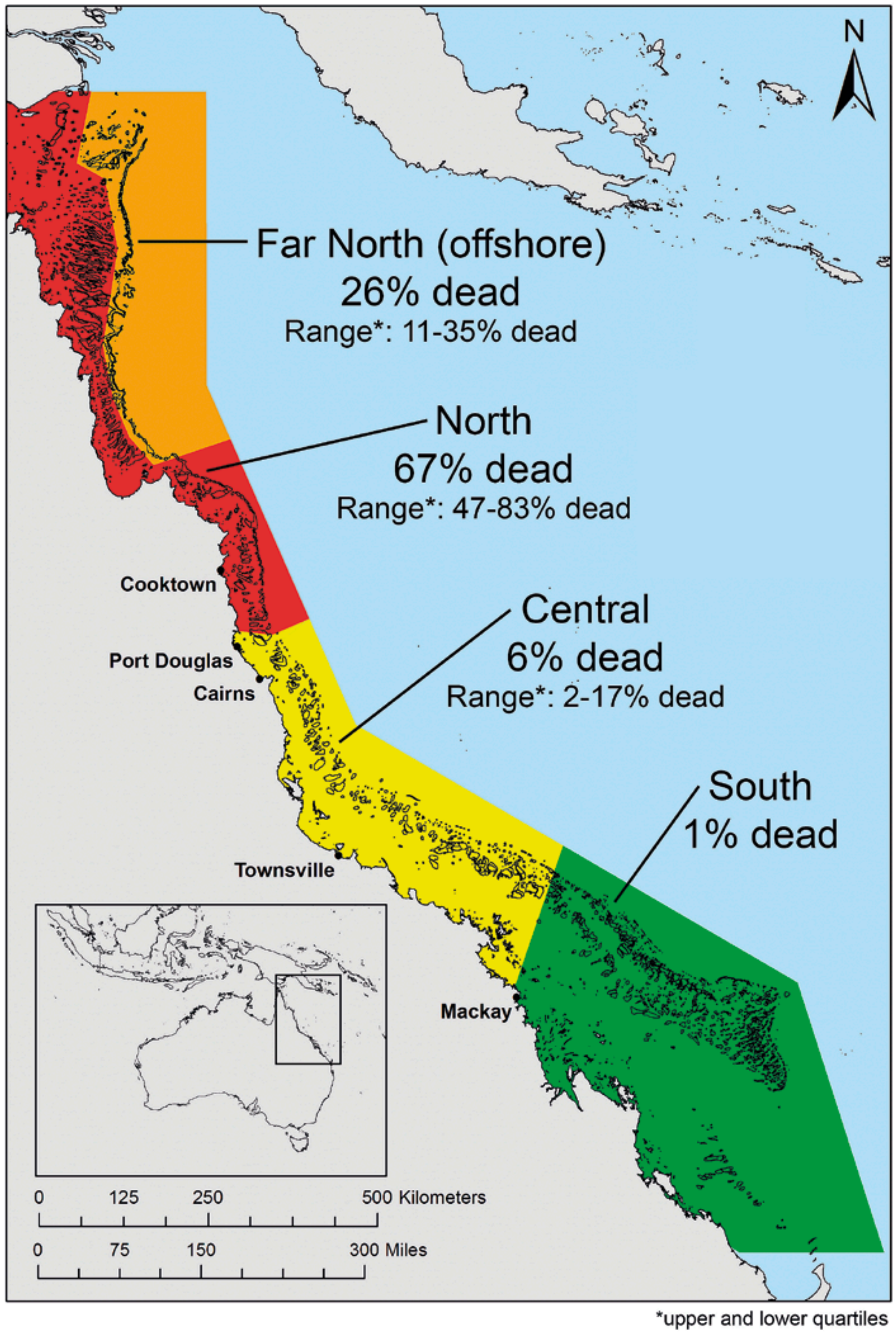

FIGURE 12.1.14 Coral loss along the Great Barrier Reef, Queensland. A survey was conducted in 2016 to estimate the extent of coral bleaching and coral loss. The north and far north regions of the reef have been affected the most by bleaching events (red and orange regions). Scientists also observed corals regaining colour in the southern part of the reef (green region). This is thought to be due to cooler waters in the southern region.

12.1 Review

SUMMARY

- Ecosystems are dynamic and changes are occurring all the time.
- A stable ecosystem is a self-regulating system, where populations are maintained through a negative feedback loop.
- Disturbances are the drivers of change in an ecosystem. The intensity and frequency of a disturbance determines its effect.
- A stable ecosystem is resilient or resistant to disturbance. A resilient ecosystem is able to recover quickly from disturbances. A resistant ecosystem can withstand disturbances.
- A relationship between disturbance and biodiversity exists where too much disturbance may impede establishment of a variety of species or where too little disturbance can allow a few species to dominate over others.
- The intermediate disturbance hypothesis proposes that high and low levels of disturbance reduce the species diversity of an ecosystem.
- Species diversity is maximised when disturbances are at an intermediate level.
- The Great Barrier Reef is becoming less stable as it endures more frequent and intense disturbances. Disturbances such as increasing sea temperature and acidity along with extreme weather events have caused stress and bleaching in corals.

KEY QUESTIONS

1 Describe the relationship between biodiversity and disturbances.

2 Explain how two interdependent factors can cause an ecosystem change, using the urchin barren example.

3 The Great Barrier Reef is a very biodiverse ecosystem faced with many disturbances. Identify some disturbances that have caused changes in the reef. What changes have they caused?

4 According to the intermediate disturbance hypothesis, what would you expect to happen to biodiversity in the Great Barrier Reef if disturbance events continue to increase in frequency and intensity?

5 Describe the system through which ecosystems self-regulate and population sizes are maintained.

6 **a** How have scientists attempted to combat urchin barrens in Tasmania?

b Can you think of any other methods that might help?

7 Describe a type of disturbance that would have a large impact on an ecosystem. Describe a disturbance that would have a small impact on an ecosystem.

12.2 Technology and evidence for past ecosystem change

Understanding ecosystems that existed in the past is a difficult task. How do we know what an ecosystem was like if we were not there to record data and make observations? Fortunately, present-day ecosystems contain information that scientists can use to understand what these ecosystems were like in the past. Using technology, scientists can reconstruct ecosystems to understand how they were during different periods of Earth's history. In this section you will learn about evidence for past ecosystem change and the technology that is used to understand it.

ROCK STRUCTURE AND FORMATION

A lot of our understanding of past ecosystems comes from Earth's crust. Discoveries from fossils and information gathered from mineral deposits and rock **strata** adds to our knowledge of what Earth was like in the past (Figure 12.2.1).

FIGURE 12.2.1 The Three Sisters rock formation in the Blue Mountains, New South Wales. The composition and structure of rock formations provides information about ecosystems of the past.

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In Chapter 10 you learnt about the process of fossilisation and how the fossil record provides insight into the evolution of organisms through geological time. The fossil record is a window into ecosystems of the past; it can tell us about the kinds of organisms that once lived, their adaptations, diet and behaviour, how abundant they were through time and the habitats they occupied.

Rocks not only preserve information about the biotic components of past ecosystems but also record the conditions of the environment throughout time. Rocks contain evidence of changes in climate, volcanic activity, atmospheric oxygen levels, sea levels, shifting landmasses and much more.

The structure of rocks gives insight into how they were formed and the conditions they have been exposed to. **Igneous rocks** are formed when magma or lava cools and crystallises. Some igneous rocks form on Earth's surface after a volcanic eruption but many form underground or underwater, on the ocean floor.

Sedimentary rocks are formed when small particles of weathered rock are compacted and cemented into layers. These layers accumulate over time and are visible as horizontal layers known as strata (Figure 12.2.1). Fossils are preserved in layers of sedimentary rock. Different environments contain different types of sediment. The sediment deposited in a swamp will be very different from the sediment in a desert. Layers of sedimentary rock are an important record of the environmental changes that have taken place throughout Earth's history.

Metamorphic rocks are formed when existing rocks are exposed to extreme heat or pressure, causing physical or chemical changes.

Each of these rock types tells different stories about the environment at the time of their formation.

Environmental conditions can also alter the structure of rocks after their formation. Physical weathering by wind, water and ice and temperature changes can cause rocks to crack or break into smaller pieces. The shape of rocks can give important clues about the environmental changes that have taken place over time. For example, valleys are formed by rivers and glaciers, and wave action wears away coastal cliffs. These environmental processes leave characteristic rock formations for thousands of years after the rivers have stopped flowing and the glaciers have melted. Geological events such as earthquakes and tectonic plate collisions also change the structure of rocks.

Rocks are a rich source of information about the past. An understanding of the structure and formation of rocks is an important step in understanding past ecosystems. Technology can be used to gain further insight into the composition and age of rocks, revealing more information about the history of Earth and the organisms that inhabit it.

RADIOMETRIC DATING

Radioactive or **radiometric dating** is a technique used to calculate the age of rocks and minerals using **radioactive isotopes**. Radioactive isotopes are elements that have an unstable nucleus. Over time the isotope decays and energy and matter are released as radiation and the element eventually becomes stable.

> Isotopes are forms of elements that have different numbers of neutrons in their nucleus, but the same number of protons (and electrons). For example, carbon-12, carbon-13 and carbon-14 are three isotopes of carbon. Carbon-12 contains 6 protons and 6 neutrons, carbon-13 contains 6 protons and 7 neutrons and carbon-14 contains 6 protons and 8 neutrons.

Radioactive decay occurs at a regular measurable rate for each isotope. A radioactive parent atom eventually decays into a stable daughter atom. This decay process is measured with a unit of time called a **half-life**. A half-life is the time it takes for half of the parent atoms in a radioactive material to turn into daughter atoms. The length of a half-life is unique to every radioactive isotope because different elements decay at different rates. For example, the half-life of carbon-14 is 5730 years while uranium-245 has a half-life of 704 million years.

A spectrometer is a scientific instrument that is used to measure the radioactivity of a particular isotope in a sample. By examining the relative amounts of parent and daughter atoms in a sample of rock or mineral, the age of a sample can be identified. For example, if 75% of the atoms in a rock sample are in the stable daughter form and 25% are still in the radioactive parent form, the rock is in its second half-life (Figure 12.2.2).

For example, if a sample was thought to be very old, uranium–lead dating could be used. Radioactive uranium-238 eventually becomes the stable daughter isotope lead-206. The half-life of uranium-238 is 4500 million years. A sample with 75% stable lead-206 atoms would leave a remaining 25% of radioactive uranium-238 atoms making the sample 9000 million years old (Figure 12.2.3).

The type of sample determines what kind of parent–daughter radio isotope dating should be used. For example, potassium–argon dating is used for molten rock and volcanic ash where potassium-40 decays into argon-30. Uranium–lead dating can be used for rocks that formed a long time ago, from millions of years to over 4.5 billion years. Carbon isotopes are used to date organic matter such as bones, wood and shells.

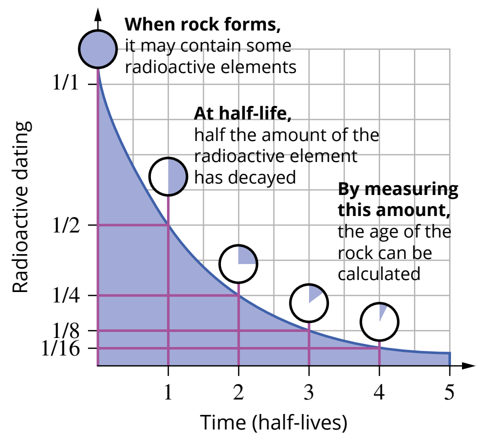


FIGURE 12.2.2 Radiometric dating uses the rate of radioactive decay to determine the age of rocks. A half-life is the time it takes for half of the parent atoms in a radioactive material to turn into daughter atoms.

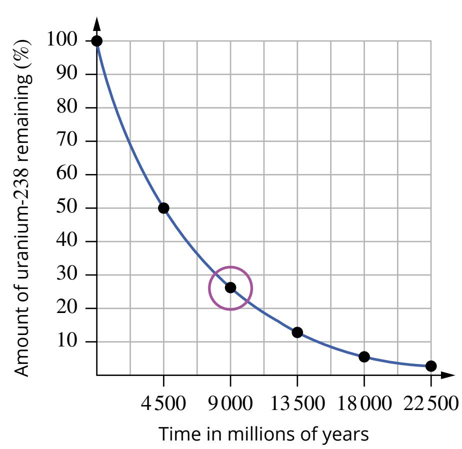


FIGURE 12.2.3 Radioactive decay of uranium-238

Carbon dating

FIGURE 12.2.4 Sample being removed from a human femur (leg bone) for carbon dating. The bone is estimated to be from medieval times (5th to 15th century).

For samples older than 50 000 years, potassium-40, which is found in volcanic rock, can be used. As the volcanic rock cools, its potassium-40 decays into argon-40 with a half-life of 1.25 billion years.

Carbon dating is used to estimate the age of organic matter that is between 5730 and 50 000 years old.

Ice cores provide information about abiotic and biotic factors in past ecosystems.

Carbon dating is a type of radiometric dating that is used to identify the age of something that was once living (Figure 12.2.4). We can use carbon dating to extract information about the age of organisms in the fossil record. By measuring the amount of carbon-14 in a sample of organic matter, we can determine when that organism was last alive. All living organisms are constantly taking in carbon. Their bodies contain two carbon isotopes: carbon-14 and carbon-12. At any given moment, all living things have approximately the same ratio of carbon-12 to carbon-14 in their bodies as in the atmosphere.

Most carbon atoms in the atmosphere are in the stable carbon-12 form and only a small amount are carbon-14. Cosmic rays from the Sun create energetic neutrons that collide with atoms in the atmosphere. Carbon-14 is created when an atmospheric nitrogen atom gains a neutron, becoming radioactive and unstable. Both carbon isotopes can combine with atmospheric oxygen to create carbon dioxide (CO_2).

Plants absorb carbon dioxide through photosynthesis and some of the carbon dioxide they absorb contains radioactive carbon-14. Animals also acquire radioactive carbon by consuming plants and other organisms. The carbon-14 in an organism is constantly decaying and being replaced. When an organism dies, it stops taking in carbon. The carbon-14 already contained in the body of the organism is not replaced and decays at a predictable rate while the amount of carbon-12 stays the same. By measuring the amount of carbon-14 and carbon-12 in a dead organism and comparing that with the amount in a living organism or the atmosphere, we can calculate how long ago the organism died.

Carbon dating cannot be used for organisms older than 50 000 years. The relatively short half-life (5730 years) of carbon-14 means the amount of carbon-14 is too small to detect after this time. Analysis of single samples can only tell us about an individual organism. With a suite of samples and data, we can learn more about changes in communities through space and time. Using this information, scientists can understand more about population booms and extinctions of species, expansions and collapses of ecosystems, and the role that fluctuating environmental conditions played in changing past ecosystems.

ICE CORE DRILLING

An **ice core** is a cylinder-shaped sample of ice that has been drilled out of a glacier or ice sheet. Examining ice cores can provide us with information about abiotic and biotic factors in past ecosystems.

Glaciers and ice sheets are formed by gradual accumulation of snow. Snowfall builds up in layers over time; more and more snow is added every year and the underlying layers of snow get compressed, eventually turning into ice.

Collecting ice core samples is a difficult process where a long vertical hole is drilled from Earth's surface and a 'core' of ice is removed from the hole (Figure 12.2.5). The ice core is like a timeline; the ice furthest away from the surface is the oldest and the ice on top is the most recent. Seasonal differences in snowfall are visible as annual bands or layers along the ice core, but these bands are more difficult to see the further they go back in time. Numerical flow models have also been developed to date ice cores more accurately. The longest ice core ever sampled is from Antarctica—it is 3 km long and dates back 800 000 years.

Evidence about past air temperatures, precipitation rates and atmospheric gases are trapped within the layers of ice. Small particles such as pollen, microbes, dissolved chemicals and air bubbles that were captured at the time of snow fall, can be extracted and used as if they were samples taken at that time. To find out information about a particular time in the past, scientists isolate the layer or layers of ice corresponding to the time frame that they want to examine.

FIGURE 12.2.5 A scientist in Antarctica extracting an ice core from a drill. Analysis of the core provides evidence of past climate change.

BIOLOGY IN ACTION CC ICT S

Gas analysis of ice cores in Antarctica

To reconstruct the past composition of Earth's atmosphere, scientists take direct measurements from ice cores. The gas bubbles trapped in an ice core can be extracted by melting or crushing the ice in a vacuum. Once released, the gas is analysed by a mass spectrometer to identify and quantify the chemistry of the trapped atmosphere. Atmospheric gases are measured in parts per million (ppm).

Using gas analysis of ice cores taken from a large ice dome in Antarctica, known as Law Dome, scientists have discovered that the concentration of greenhouses gases, such as carbon dioxide (CO_2) and methane, has increased dramatically in the last 100 years. This has occurred alongside the increased use of fossil fuels since the beginning of the Industrial Revolution in the mid-1700s. Humans have continued to burn increasingly large amounts of coal, oil and gas for power, which releases carbon dioxide into the air.

The Law Dome ice cores provide a record of greenhouse gas concentrations from 1006 to 1978. A record of direct measurements of the composition of the atmosphere from the 1970s until the present day also exists. Direct records of atmospheric carbon dioxide and air temperature are presented alongside carbon dioxide records from Law Dome ice cores in Figure 12.2.6. The Law Dome ice core carbon dioxide records show a substantial rise in atmospheric levels since the 1800s (Figure 12.2.6a). Atmospheric composition records of the recent past show that carbon dioxide levels in the atmosphere have continued to steadily increase since the early 1900s (Figure 12.2.6b).

Ice cores can also be used to reconstruct changes in Earth's climate and temperature that occurred in the past. Temperature cannot be measured directly but is inferred from the isotopic composition of water molecules, which are released when an ice core melts.

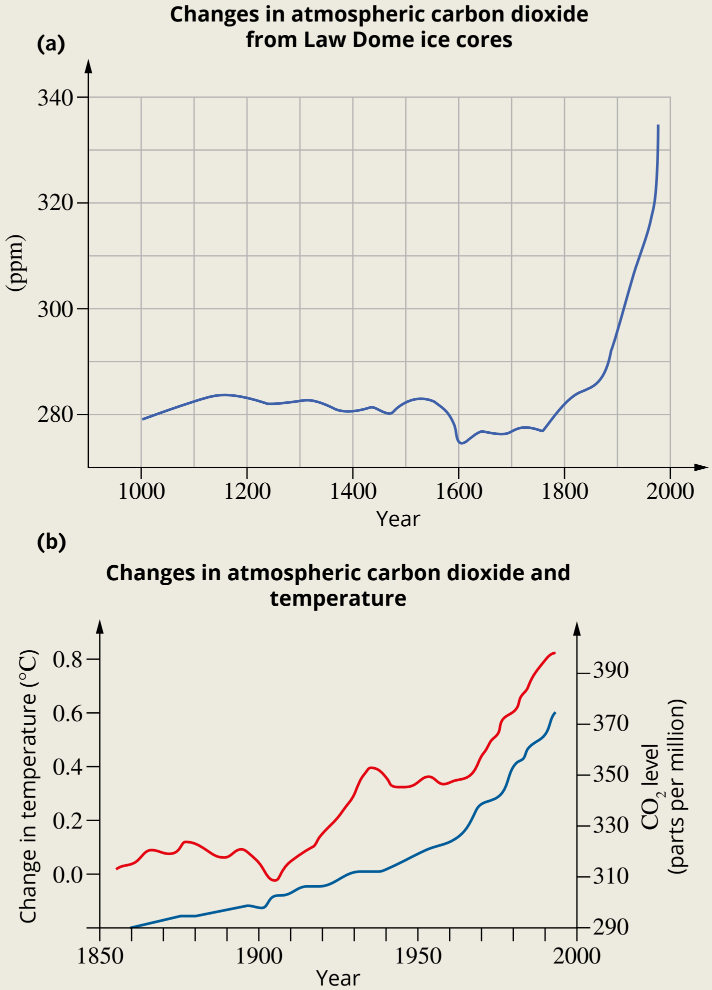


FIGURE 12.2.6 (a) Concentration of CO_2 measurements taken from trapped air in Law Dome ice cores. (b) Changes in atmospheric CO_2 (blue line) and air temperature (red line) between the years 1850 and 2000. This data is taken from direct measurements of atmospheric CO_2 and air temperature.

HUMAN RECORDS

Along with using geological evidence, we can examine ancient human records to understand ecosystems of the past. Ancient humans may not have recorded observations in the same way or for the same scientific purposes as we do today, but the records of our **ancestors** still hold a wealth of evidence about ecosystem change.

Australia is home to one the oldest lineages of modern humans and culture. By examining the historic **artefacts** of Indigenous Australians, we can collect information about Australia's natural history and gain insight into the changes that occurred in the ecosystems of Australia's past.

Indigenous Australian art

FIGURE 12.2.7 An Indigenous Australian rock painting depicting a thylacine-like animal at the Ubirr rock site in Arnhem Land, Northern Territory. Rock paintings at the Ubirr rock site have been dated to between 1500 and 28 000 years ago, with most paintings dated to approximately 2000 years ago.

Australia has some of the oldest artistic images in the world, with a long tradition of rock painting and engravings. **Rock paintings** created by Indigenous Australian people date from modern time back to 28 000 years ago. Rock painting is a significant part of the history and culture of Indigenous Australian people and is an important record of the people and the places they lived.

Ancient art usually depicts the types of animals that were abundant or important at the time the artwork was created. Examining the subject matter of the ancient rock paintings of Indigenous Australians can tell us about the diversity of species at that time, where they lived in the past and changes in animal communities over time.

For rock paintings to be used in reconstructing past ecosystems we must understand two things: what is depicted in the artwork and the age of the rock art. Using radiometric dating, it is possible to discover the age of the rock painting. Samples of pigments may be taken directly, but this method can be destructive to the artwork. To preserve a rock painting a sample of material overlying the artwork, including sediments or mud, can be taken. In northern Australia mud-wasp nests overlying rock paintings have been used to date rock paintings underneath. Carbon dating was used to estimate the age of the wasp nest as approximately 17 000 years old. This indicates that the rock paintings underneath the wasp nest is at least 17 000 years old.

Rock paintings found in Arnhem Land in the Northern Territory depict species that are no longer found in that area and species that are Extinct. Representations of animals that look like the Tasmanian devil (*Sarcophilus harrisii*), thylacine (*Thylacinus cynocephalus*) and numbat (*Myrmecobius fasciatus*) provide evidence that these animals existed alongside the communities of Indigenous Australians in Arnhem Land between 1500 and 20 000 years ago (Figure 12.2.7). It is thought that the thylacine became Extinct on mainland Australia between 2000 and 3000 years ago and colonial documentation suggests the species was only found in Tasmania by the time Europeans colonised Australia. Rock paintings from across Australia indicate that the thylacine once had a much broader distribution on mainland Australia, providing evidence that has helped scientists reconstruct the historical distribution of this species.

WS 4.6

Ubirr is a rock site in Kakadu National Park in the Northern Territory that has a rich collection of Indigenous Australian rock paintings. Most of the paintings at this site have been dated to approximately 2000 years ago, a time that is known as the freshwater period in that region. The rock paintings depict a time of abundant food supply with many images of fish, mussels, waterfowl and goannas. The collection of the rock paintings at Ubirr provides an important record of the local ecosystems 2000 years ago and helps us to understand the changes that have occurred in the region since.

Middens

Studying how humans lived in the past can tell us a lot about the way they interacted with the environment and the populations of organisms that existed at the same time. A **midden** is a historic site of human occupation where people left debris from their meals (Figure 12.2.8). In Australia, the middens of Aboriginal and Torres Strait Islander people contain animal remains such as sea shells and bones.

Studying the contents of middens can indicate the main food sources that made up the human diet and how it may have changed across different seasons or over a long period of time. Some middens were used by many generations of people and can be metres deep. The size of a midden depends on the length of occupation at that site. Middens are mostly found on the coast or near lakes, rivers and estuaries. Lake Mungo is a dry lake in south-west New South Wales and is a rich archaeological site providing a window into the lives of the Indigenous Willandra people. The remains of fish, shellfish, yabbies and mammals have been found in middens around Lake Mungo. Evidence of human habitation near Lake Mungo dates back to 50 000 years ago.

Middens are distinct from natural deposits of shells and bone because they contain a high proportion of mature, edible species. Natural shell bed deposits include juveniles and inedible species.

FIGURE 12.2.8 A midden created by Indigenous Australians in Stephens Bay, Tasmania. Middens provide evidence of the food sources that local people used at different times in the past.

The rock art and middens of Indigenous Australians provide rich information about species diversity and ecosystems in the past.

BIOLOGY IN ACTION AHC S

Disappearance of shellfish reef ecosystems since European settlement

European colonisation in Australia has had a vast impact on many ecosystems. Shellfish reefs are no exception, with 90% of these ecosystems now considered damaged or destroyed. Early colonial dredging practices are thought to have played a major role in the destruction of these reefs along with commercial exploitation of shellfish up until the 1970s. Unfortunately, historical records about the composition of the pre-European shellfish reef environments are hard to come by. Scientists John R Ford and Paul Hamer have attempted to document the loss of shellfish reef ecosystems in Victoria by examining the composition of middens in Victoria's coastal areas.

Their observations have helped to reconstruct species assemblages of the Victorian shellfish reef systems confirming that the reefs were once dominated by blue mussels and flat oysters. Despite the end of dredging and shellfishing practices in this area, these species have not recovered. Mussels and oysters play an important role in water purification of marine ecosystems and re-establishing these shellfish reefs would improve the water quality of the area. A project has now been set up to attempt to reintroduce these shellfish back into Port Philip Bay in Victoria by deploying large numbers of juveniles at three sites in the bay (Figure 12.2.9).

FIGURE 12.2.9 A nursery bed of blue mussels (*Mytilus galloprovincialis*) on an exposed rock at low tide at Blairgowrie, Victoria

12.2 Review

SUMMARY

- The structure and formation of rocks gives important clues about the geological history of Earth and changes in its environment.
- The fossil record is an important source of evidence for the evolution of organisms and ecosystem change.
- Rock strata in sedimentary rocks provide a record of the environmental conditions at the time each layer of sediment was formed.
- Weathering of rocks by water, ice, wind and temperature changes provides evidence of environmental processes and conditions over time.
- Radiometric dating relies on isotopic decay.
- The decay of radioactive isotopes is measured in a unit of time called a half-life, which is different for each type of isotope.
- Carbon dating is used to date organic matter of organisms that were once living.
- Ice core drilling and gas analysis can tell us about past atmospheres and global temperatures.
- Indigenous Australian rock art can help us understand the distributions of species in the past and features of the local ecosystems that were culturally significant.
- Middens are historic sites of human occupation where debris from meals was left. Middens provide useful information about the diversity of species in past ecosystems.

KEY QUESTIONS

1. **a** Compare the processes of rock formation for the three rock types igneous, sedimentary and metamorphic.
   b Which rock type is most likely to preserve the remains of organisms? Justify your answer.
2. Which carbon isotopes are used in carbon dating and how are they used?
3. Which of the following statements about carbon-14 dating is incorrect?
   A It measures the rate of decay from carbon-12 to carbon-14.
   B It requires organic matter to be present in the fossil.
   C It is limited to dating fossils that are less than about 50 000 years old.
   D It is an absolute measure of dating fossils.
4. Carbon-14 (^{14}C) decays to nitrogen-14 (^{14}N) with a half-life of approximately 5730 years. If a sample of material contained 10 000 atoms of ^{14}C 30 000 years ago, what is the approximate number of ^{14}C atoms that it will contain today?
   A 5000
   B 1250
   C 312
   D 156
5. What information can ice core drilling tell us about past environments?
6. How can rock art inform us about past ecosystems?
7. How does analysis of middens contribute to understanding past ecosystems? Give an example.
8. How are ice cores formed and extracted?
9. Briefly explain the process of reconstructing past atmospheres from an ice core.
10. What trend in atmospheric carbon dioxide levels do the Law Dome ice cores and past direct measurements display?

12.3 Living evidence of ecosystem change

Examination of current ecosystems and living populations of organisms can inform us about changes in the recent past and long ago. Comparison of present-day plant and animal species with their ancestors can provide insights into the way Australia's climate and environment has changed and influenced evolution. The extinction of species indicates that these species were not as well adapted to ecosystem change as those that persist today.

GONDWANA: ANCIENT SUPERCONTINENT

In Australia, the evolution of **sclerophyll plants** and small mammals provides evidence for historic climate change in Australia. Australia was once connected to a tropical supercontinent called **Gondwana**, which included most of the land masses found in today's Southern Hemisphere (Figure 12.3.1).

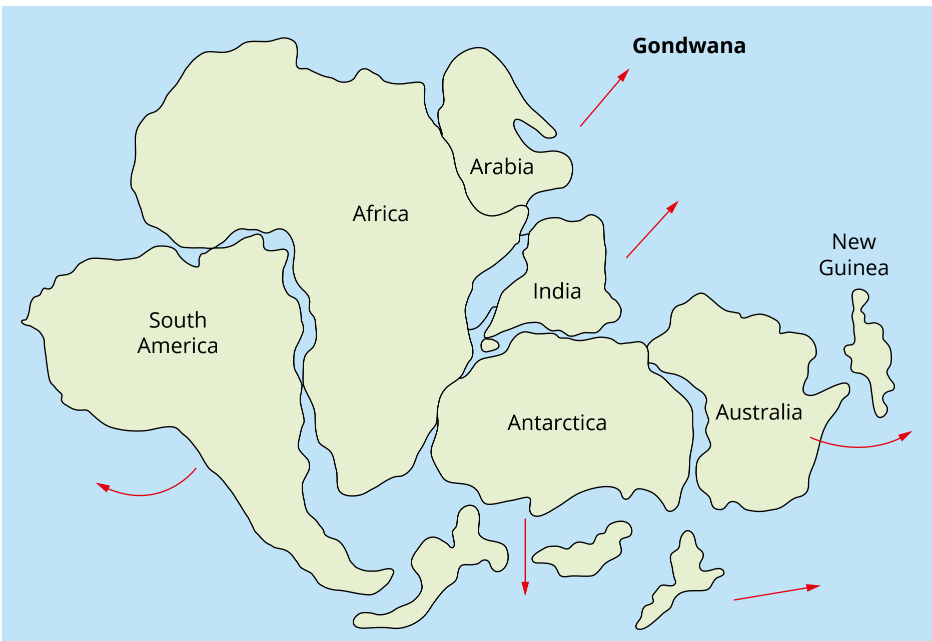


FIGURE 12.3.1 Australia was once part of the supercontinent, Gondwana. During this time, Australia was mostly covered in tropical rainforest. Over the period of 132–96 million years ago, the Australian continent separated from Gondwana and drifted north, becoming drier.

Over the period of 132–96 million years ago the land mass that now forms Australia separated from Gondwana. Australia completed its separation from Antarctica 30 million years ago and has been isolated from other land masses since. Initially Australia was warm and humid. Fossil evidence shows that most of the country was dominated by tropical rainforest habitat. This is hard to imagine in present-day Australia where desert and semi-arid environments are dominant.

After Australia's separation from other land masses it drifted north and its weather patterns changed; temperatures increased and rain became more seasonal. These changes eventually led to long-term changes in climate and the arid environment that we see in Australia today. Surviving pockets of tropical rainforest still exist in Australia and contain the same kind of species that might have been present on Gondwana 100 million years ago. One of the most extensive surviving pockets of Gondwana rainforest is in the Gondwana Rainforests of Australia World Heritage Area, in New South Wales and Queensland (Figure 12.3.2). Many species that are found in Australia today evolved from these early tropical Gondwanan species.

Australia was once part of the tropical supercontinent, Gondwana. Australia separated from Gondwana over the period of 132–96 million years ago. Relics of Gondwana rainforests still exist today in small regions.

Australia drifted north after separating from Gondwana and became drier. Many of Australia's plant and animal species are adapted to its dry conditions.

FIGURE 12.3.2 The rainforests of Dorrigo National Park in New South Wales still contain ancient species from the time of Gondwana. Dorrigo National Park is part of the Gondwana Rainforests of Australia World Heritage Area. These important ecosystems are a window into Australia's past.

ADAPTATIONS TO CHANGING ECOSYSTEMS

Adaptations of present-day species indicate the drivers of change that have acted on them in the past. A comparison of living species and their ancestors indicate past selection pressures.

Sclerophyll plants

FIGURE 12.3.3 Sclerophyll woodland in the Northern Territory, Australia

Sclerophyll plants are well adapted to harsh, dry climates and nutrient-deficient soils (Figure 12.3.3). They have hard, tough leaves and some contain toxic or indigestible chemicals, making them unpalatable to herbivores. Sclerophyll plants include *Eucalyptus* and *Acacia*, the dominant shrubs and trees found throughout the forests, savannahs and scrubland of present-day Australia. Today there are more than 800 species of *Eucalyptus* and 900 species of *Acacia* found in Australia. *Eucalyptus* and *Acacia* originated between 50 million and 35 million years ago, but few species existed during this time and their distribution was limited.

The spatial spread and speciation of *Acacia* and *Eucalyptus* coincided with an increase of charcoal deposits in the fossil record about 20 million years ago. Incidences of fire increased as the Australian climate became hotter and drier. Rainforests declined and Gondwanan species were restricted to small areas of the country where there was higher rainfall and sufficient soil nutrients. Sclerophyll plants being well adapted to more arid conditions began to diversify to take advantage of the newly opened **ecological niches** where rainforest species could no longer survive.

Small mammals and kangaroos

FIGURE 12.3.4 Red kangaroo (*Macropus rufus*) displaying bipedal hopping locomotion

Australia's shift to a drier, hotter climate and the spread of arid-adapted vegetation also affected mammal species. When rainforests dominated Australia, mammal diversity was at its peak. The rainforest was home to the ancestors of modern mammal groups that are now found in drier parts of Australia. Many small, **arboreal** (tree-dwelling) mammals existed, living in trees. As climate change occurred and the vegetation changed from tropical rainforest to more open sclerophyll forest and grasslands, tree-dwelling mammals became limited to pockets of rainforest and larger ground-dwelling animals began to dominate.

The evolution of the kangaroo species that are found all over Australia today follows this pattern. Around 25 million years ago ancestors of the kangaroo existed in the rainforest. Their ancestors were arboreal and had possum-like features, climbing up trees and running through the forest floor on all fours.

Between 15 million and 20 million years ago kangaroo species diversified and expanded their range, taking over open woodlands and grasslands. As arid areas continued to increase, the kangaroo ancestors adapted to moving on just two legs (bipedal locomotion) and their teeth adapted to grazing on grass and tough sclerophyll plants. The red kangaroo (Figure 12.3.4) appeared about 2 million years ago and became increasingly successful as other large herbivores began to die out.

FIGURE 12.3.5 *Procoptodon goliah*, an Extinct giant relative of modern kangaroos. It reached 3 m tall and walked on its hind legs.

The success of modern kangaroos might be attributed to their ability to hop. Hopping is a very efficient way to move, allowing kangaroos to cover large distances without expending much energy. This adaptation would have helped the kangaroo reach food and water quickly as these resources became scarce and farther apart with a drying climate. Hopping locomotion would have been much easier and more advantageous in open woodlands and grasslands than in dense rainforest. Kangaroo-like **megafauna** that existed alongside modern kangaroos include *Procoptodon goliah*, which was up to 3 m tall and weighed up to 240 kg (Figure 12.3.5). These large animals disappeared about 15 000 years ago and are thought to have walked upright instead of hopping.

The closest surviving relative of early kangaroos is the musky rat kangaroo which evolved 20 million years ago. The musky rat kangaroo still exists today in the tropical rain forests of north-east Australia. It is a small marsupial that retains some of the ancestral possum-like features, which have been lost in modern kangaroos. The musky rat kangaroo is well adapted to life in the dense forest. Its hind feet have grooves on the pads and a mobile first toe, which help it to climb through the undergrowth and obstacles of the forest floor.

LOCALISED EXTINCTION

Local extinctions are evidence for ecosystem change. **Local extinction** (also known as extirpation) occurs when a population of a particular species ceases to exist in an area of its former range, but other populations of the species still exist elsewhere. When a species persists in one area but its numbers have declined in another area, we can infer that a selection pressure is occurring in one habitat that is not occurring in other areas. Species with specialised requirements for diet or habitat are more susceptible to **selection pressures** and ecosystem change.

By examining local extinctions, it is possible to identify potential threats to a species as a whole. Factors leading to extinction are often complex and may be acting independently or together. Local extinctions are more likely to occur when populations become fragmented and migration of individuals in and out of an area is limited.

For example, in Australia koalas (Figure 12.3.6) have a large distribution from north-eastern Queensland through New South Wales and Victoria to a small part of South Australia. The national distribution of koalas has not drastically reduced since the end of the fur trade in the 1927, but individual populations have declined and local extinctions have occurred since this time. Koala populations have become fragmented and increasingly isolated from one another due to land clearing and road construction for urban development (Figure 12.3.7). Land clearing creates **habitat fragmentation**, which isolates koala populations. Population isolation prevents the migration of individuals and genes between populations, creating pockets of smaller, less-diverse populations that are more vulnerable to selection pressures, such as disease, drought and extreme heat. Urbanisation and the development of roads also increases the mortality of koalas due to vehicle strikes and dog attacks.

Species that have suffered local extinctions may be good candidates for reintroduction to their habitat once the threatening processes have been eliminated. It is important to identify the selection pressure or ecosystem changes that caused the local extinction before reintroducing the species. Once the selection pressure is managed or removed the species can be reintroduced into the same habitat. It is also possible to introduce species to new areas if the habitat is suitable and there are no threatening processes present.

FIGURE 12.3.6 Koalas (*Phascolarctos cinereus*) are experiencing localised extinctions throughout Australia due to habitat fragmentation caused by deforestation and urban development.

Localised extinctions are becoming more common as habitat is fragmented and urban development spreads.

FIGURE 12.3.7 Fragmentation of koala habitat from urban development on the Gold Coast, Queensland

BIOFILE CC S

Greater bilby range reduction

The greater bilby (*Macrotis lagotis*) (Figure 12.3.8) was once distributed over approximately 70% of Australia in arid and semi-arid regions. Now the greater bilby occupies only 20% of its previous range and is found in patchy isolated populations in the Northern Territory and Western Australia, and in a small area of Queensland north of Birdsville (Figure 12.3.9).

A number of factors have contributed to local extinctions of the greater bilby such as loss of habitat, hunting, predation and competition from introduced species. The spread of agriculture has drastically changed the greater bilby's habitat. Tree clearing and crops have made most of the species' former range unsuitable and the introduction of grazing animals such as cattle, sheep and rabbits has put the greater bilby in direct competition for food resources and burrows. Introduced predators including foxes and cats have added to the declines in greater bilby numbers as well.

Conservation efforts to increase populations of the greater bilby include captive breeding programs and reintroduction to some areas of the greater bilby's former range. The most successful reintroduction site has been into a 52 km^2 reserve with a 1.8 m high exclusion fence that prevents foxes and cats from entering the reserve.

FIGURE 12.3.8 The greater bilby (*Macrotis lagotis*) has a limited range size due to may local extinctions. Efforts are being made to reintroduce the greater bilby to areas of its former range.

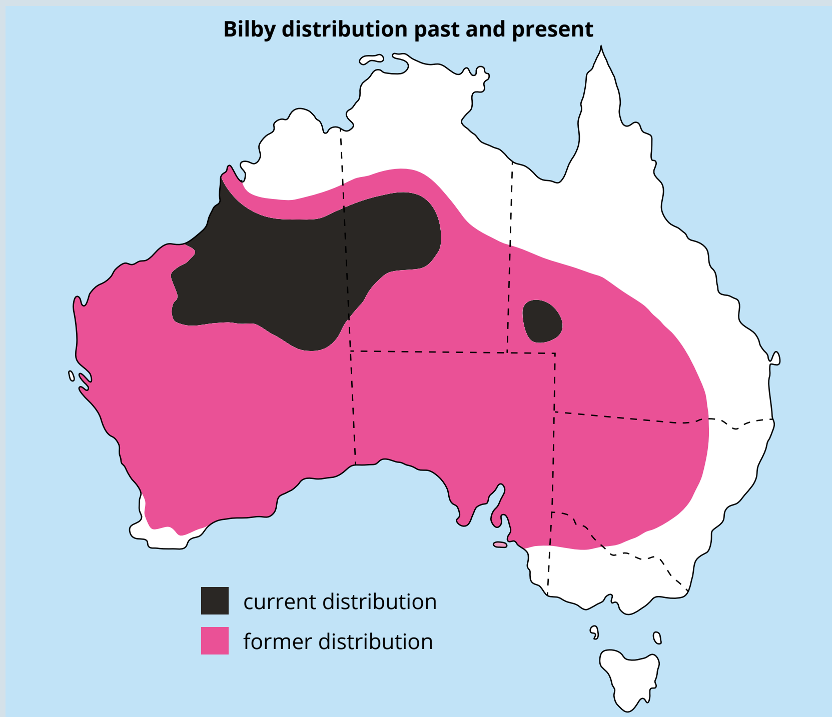


FIGURE 12.3.9 The past and present distributions of the greater bilby (*Macrotis lagotis*) in Australia. The greater bilby has undergone a significant reduction in its range since European settlement.

FIGURE 12.3.10 Feral goats are one of the most damaging invasive species in New South Wales. Goats overgraze vegetation, damage soil and compete with native herbivores in areas where their population numbers are high.

INVASIVE SPECIES CHANGE ECOSYSTEMS

Invasive species are organisms that are able to establish populations outside their natural ranges. These species are not normally part of the ecosystem where they have become established, and their ability to maintain a self-sustaining population can have drastic consequences for native biodiversity and ecosystems (Figure 12.3.10). Most species that are introduced to a new ecosystem or habitat do not establish and invade, but when they do the effects on ecosystems are often difficult to reverse and can have long-term conservation and economic impacts. For example, the introduction of a parasitic insect to an agricultural ecosystem could destroy crops and cost the agricultural industry millions of dollars. For these reasons, many countries have strict **biosecurity** laws to prevent potentially invasive species crossing their borders.

Invasive species pose a threat to ecosystems when their success in a new environment displaces the native species of that area. Invasive species have the largest impact on island and isolated ecosystems because species in these ecosystems have evolved in isolation, are often highly specialised and have had very few encounters with new species. New species coming into these vulnerable ecosystems often have few natural predators or competitors and niches in the community may still be vacant. These features make islands and other isolated areas very susceptible to invasion when a new species arrives.

Invasive species are examined in more detail in Chapter 13.

GO TO ➤ Section 13.1 page 575

BIOLOGY IN ACTION CCT S

Common brushtail possum invasion of New Zealand

We often hear of the problems that introduced plants and animals cause in Australia, but Australian species can also be considered invasive pests when they arrive in other parts of the world. The common brushtail possum (*Trichosurus vulpecula*) was introduced to New Zealand in the 1850s when it was deliberately introduced for use in the fur trade (Figure 12.3.11). The species is now found throughout New Zealand in large numbers, where it has successfully established populations by moving into the largely vacant niche for a large, tree-dwelling, mammalian omnivore.

FIGURE 12.3.11 Brushtail possum (*Trichosurus vulpecula*), sitting on a tree branch in New Zealand. The brushtail possum is an invasive species in New Zealand and poses a significant ecological threat to the country's native species.

The common brushtail possum is considered a major ecological threat in New Zealand because of the extensive damage it causes to native vegetation and animal species. Brushtail possums feed on the leaves, flowers and buds of native New Zealand forest species, which evolved without foliage-eating mammals. New Zealand's plants are very palatable and have no natural defence against the possums whose numbers are currently around 30 million. New Zealand's possum population is capable of eating about 21 000 tonnes of foliage each night destroying a lot of forest habitat and food sources, such as flower nectar, for native species. Brushtail possums also affect New Zealand's animals directly; they have been recorded eating the eggs, chicks and occasionally adults of many native bird species that evolved, in isolation, without any mammalian predators.

The brushtail possum is successful in New Zealand for a number of reasons. It is a tolerant, **generalist** species and the ecosystems of New Zealand provide abundant food resources, habitat opportunities and protection from predation. The brushtail possum has a generalist diet compared to most marsupials; it feeds on leaves, flowers, fruit, insects and bird eggs. In New Zealand, the brushtail possum has very few competitors for food and habitat; the only native land mammals in New Zealand are three species of bats that mostly eat small insects. In Australia, the brushtail possum would be competing with other marsupials with similar diets and habitat requirements, restricting its range and numbers. The brushtail possum's numbers are also controlled by predators in its native Australian habitat, such as dingoes, goannas and eagles. None of these predators are found in New Zealand and the possum continues to thrive, destroying native vegetation and fragmenting the habitats of native New Zealand animals.

BIOLOGY IN ACTION EU S

Controlling the invasive common brushtail possum in New Zealand

Large-scale management operations of the common brushtail possum in New Zealand combine a number of control methods including hunting, trapping and poisoning. New Zealand spends $110 million per year on possum control. Improving technologies helps to maximise management efforts and bring down the cost of this large expense. Research into the best pest control methods are very important for the survival of New Zealand's forests and native animal species.

Ground control and aerial control are the two widely used approaches for possum and other invasive mammal management in New Zealand. Ground control involves setting up poison bait stations and traps on forest floors and at the base of trees (Figure 12.3.12). Aerial control is required for areas that are too difficult to reach on foot. Sodium monofluoroacetate (1080) poison baits are dropped from a helicopter or small plane over pest-affected areas; it is a cost-effective but less targeted method of pest species control. Ground control is very effective but labour intensive and expensive, as the traps and bait stations have to be distributed on foot. Another reason traps have a high labour cost is that most have to be reset after each kill.

New Zealand inventors have created a new possum-trapping system which is able to kill many possums before it needs to be reset. The traps are mounted on tree trunks and have an attractive scent that lures the possum to run up the tree. The possum then puts its head into the trap and pulls on a bite block to trigger the trap. The trap strikes the possum and kills the animal instantly. The trap resets itself and can be used again until the gas canister that powers the trap's piston runs out. These traps are a viable alternative to poisoning as they are effective and cause less suffering. These traps are available for anyone to buy so local communities and individuals can aid in the national effort to control possums.

FIGURE 12.3.12 Sign warning visitors of pest control operations in the coastal forests of the Aupouri Peninsula, North Island, New Zealand

12.3 Review

SUMMARY

- Adaptations of present-day species are the result of past selection pressures.
- Sclerophyll plants in Australia evolved from ancestral tropical Gondwana species. This is evidence of past climate change and increased aridity in Australia.
- The kangaroo and its relatives evolved from small arboreal (tree-dwelling) rainforest species. This is evidence of Australia's tropical past.
- Localised extinction demonstrates localised selection pressures.
- Invasive species pose a threat to ecosystems when their success in a new environment displaces the native species of that area.
- Invasive species can cause extensive, long-term damage to ecosystems.

KEY QUESTIONS

1 Describe some of the past changes in Australia's climate.

2 How do sclerophyll plants represent past climate change in Australia?

3 How do present-day kangaroos differ from their tropical ancestors?

4 How can habitat fragmentation cause localised extinction?

5 **a** Identify three disturbance factors that have contributed to range reduction and low population numbers of the greater bilby (*Macrotis lagotis*).

b Describe the conservation efforts helping to re-establish the greater bilby in areas where it has become extinct.

Chapter review

12

KEY TERMS

ancestor
anthropogenic change
arboreal
artefact
biodiversity
biosecurity
carbon dating
competitive exclusion
disturbance
ecological niche
ecosystem
generalist
Gondwana
habitat fragmentation
half-life
ice core
igneous rock
intermediate disturbance hypothesis (IDH)
invasive species
local extinction
megafauna
metamorphic rock
midden
negative feedback loop
positive feedback loop
radioactive decay
radioactive isotope
radiometric dating
resilient
resistant
rock painting
sclerophyll plant
sedimentary rock
selection pressure
small mammal
stratum (pl. strata)

REVIEW QUESTIONS

1 How are populations maintained in a stable ecosystem?

2 Give an example of a negative feedback loop in ecosystem dynamics.

3 What is ecosystem disturbance?

4 Give three examples of natural disturbance events.

5 Give three examples of anthropogenic disturbances.

6 Describe resistance and resilience in ecosystems.

7 Explain the intermediate disturbance hypothesis, using an example.

8 What causes coral bleaching?

9 What are two main ways ocean acidification negatively affects coral reefs?

10 List three reasons the coral cover of the Great Barrier Reef has decreased in the last 30 years.

11 What is radiometric dating?

12 What is carbon dating used for?

13 You estimate that a certain fossil is at least several million years old.

a Can you use carbon dating to determine its age?

b If not carbon dating, then which form of radiometric dating would you use?

14 How do animals acquire radioactive carbon?

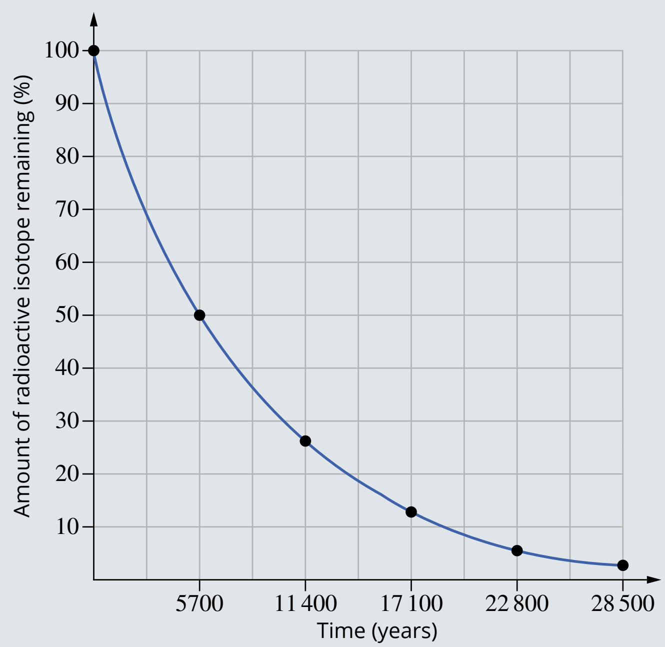
15 Which radioactive isotope is represented in the following radioactive decay curve?

A potassium-40

B uranium-238

C carbon-14

D lead-206



16 The radioactive isotope represented in the graph is suitable for estimating the age of which of the following samples?

A molten rock from the Devonian period

B skeletal remains that are thought to be 10 000–20 000 years old

C gold jewellery from the Renaissance (14th to 17th century)

D stone artefacts used by *Homo erectus*

17 What information can be gained from examining ice cores?

18 What can ancient Aboriginal rock paintings tell us about past ecosystems in Australia?

19 For rock paintings to be used in reconstructing past ecosystems, what must be understood about the art?

20 Indigenous Australian artwork holds important clues about past ecosystems.

a Look carefully at the image below and describe what the landscape in the local area might have been like when the artwork was created.

b Identify at least one important feature in the artwork and explain why this may have been important to Indigenous Australians in this community at the time.

21 Describe a midden and what it can tell us about past ecosystems.

22 What type of climate did Australia have when it was still part of Gondwana and how did it change after its separation?

23 Describe an adaptation of sclerophyll plants.

24 **a** Which types of mammals became dominant when grasslands and sclerophyll forests spread across Australia?

b Which types of mammals became more restricted when grasslands and sclerophyll forests spread across Australia?

25 What adaptations allowed kangaroos to become successful in arid Australia?

26 Describe what is meant by localised extinction (extirpation)? Give two Australian examples.

27 After completing the Biology Inquiry on page 544, reflect on the inquiry question: How do selection pressures within an ecosystem influence evolutionary change? Outline how changes to Australia's climate over the past 100 million years have influenced evolutionary change in the native flora and fauna.

CHAPTER 13

Future ecosystems

This chapter examines how changes in past ecosystems can inform the management and conservation of present and future ecosystems. You will investigate how human activities can impact an ecosystem, causing selection pressures that lead to species extinction and ecosystem change.

While human activities continue to cause significant biodiversity loss, humans also play an important role in protecting and restoring ecosystems. You will learn about the models that humans use to monitor and predict the future impacts of changing climates on biodiversity and ecosystems. You will then develop an understanding of why and how we conserve biodiversity by looking into the practices humans use to restore damaged ecosystems, country or place.

Content

INQUIRY QUESTION

How can human activity impact an ecosystem?

By the end of this chapter you will be able to:

- investigate changes in past ecosystems that may inform our approach to the management of future ecosystems, including:
  - the role of human-induced selection pressures on the extinction of species (ACSBL005, ACSBL028, ACSBL095) AHC S
  - models that humans can use to predict future impacts on biodiversity (ACSBL029, ACSBL071) AHC S N
  - the role of changing climate on ecosystems S
- investigate practices used to restore damaged ecosystems, Country or Place, for example: AHC S
  - mining sites
  - land degradation from agricultural practices

13.1 Human-induced changes leading to extinction

BIOLOGY INQUIRY CCT ICT S WE

Shifting the balance

How can human activity impact an ecosystem?

COLLECT THIS…

- large sheet of paper
- coloured pens or pencils
- tablet or computer to access the internet

DO THIS…

1. Working in pairs, choose one of the following case studies.
   - **a** Kangaroo population management and agricultural irrigation
   - **b** Introduction of foxes and cats to Australia
   - **c** Agricultural run-off in Tasmanian kelp forests
   - **d** Anti-fouling paint on boats and the effect on sea snails (whelks)
2. Spend 10 minutes researching your case study. Consult at least three online secondary sources. Note:
   - **a** the substance or pest introduced into the ecosystem
   - **b** the organism directly affected
   - **c** organisms indirectly affected (i.e. prey, predator or competitor)
   - **d** possible solutions to the problem.
3. Once you understand your case study, draw a concept map illustrating the process, including the components you identified in step 2.
4. Swap concept maps with someone working on a different case. Explain your case studies to each other. Once you understand each other's case studies, swap to another pair and repeat the process until you have understood all four case studies.
5. As a class, discuss how the impacts of human activities in ecosystems can be reduced or managed.

RECORD THIS…

Describe the way that each level of the ecosystem is affected.

Present your case study as a concept map.

REFLECT ON THIS…

How can human activity impact an ecosystem?

How can humans reduce their impact on an ecosystem?

Can humans introduce new components (e.g. substances or species) into an ecosystem safely?

Understanding causes of past **extinction** events is essential in preventing further extinctions and loss of biodiversity. In most cases a combination of factors contribute to the decline or extinction of a species. Species extinctions have been occurring since the beginning of life on Earth. An estimated 30 billion species have existed since early multicellular life forms evolved and only about 0.1% exist today. Extinction is a normal and natural part of the evolution of life on Earth. A base rate of extinction describes the historically typical rate of loss of species on Earth. There have been five mass extinction events in Earth's past where the rate of extinction

markedly exceeded the base rate and was very high through a short period of time. Causes included volcanic activity, asteroid impact, and changes in climate, sea levels and atmospheric and oceanic chemistry. It seems we are currently witnessing another mass extinction event where species are being lost at 1000 to 10 000 times the base rate.

In any ecosystem where one population or species suddenly thrives, others become displaced. This is currently occurring on a global scale as the human population continues to soar and many other species disappear. People's ability to spread out all over the world, utilising and changing the environment, creates **anthropogenic pressure** on other species. Anthropogenic pressures are caused by human activity and restrict the range of other species whose population numbers and **genetic variation** may eventually become so low the species becomes extinct. The primary threat to biodiversity and causes of extinction are habitat destruction, invasive species, pollution, overexploitation and climate change.

HABITAT DESTRUCTION

Habitat destruction is a leading cause of the global loss of **biodiversity** and of species extinction. Habitat destruction occurs when human activities alter or remove a natural habitat and the organisms previously existing in the habitat can no longer survive. More than 50% of Earth's land area has been modified by human land use changes and all aquatic environments have been affected. The main reason humans change natural habitats is to sustain our ever-increasing human population. With advances in technology, the life-span and the survival and reproduction rates of humans are increasing. Natural habitats are changed or destroyed to harvest **resources** so that the human population has food, water, energy and a place to live.

Reasons for habitat destruction include:

- agriculture, through the conversion of complex habitats to sustain only a few species of crops or livestock
- mining and oil, gas and geothermal exploration and development
- logging, which involves clearing areas of forest for timber
- urbanisation and infrastructure development, creating urban areas and road networks
- water body restructuring that diverts natural water flow and storage for irrigation and livestock and for drinking water for towns and cities
- trawling and dredging, fishing practices that alter the ocean floor
- waste disposal areas used as landfills or dumping grounds for toxins and nuclear waste
- outdoor recreation, with humans accessing more remote areas for activities (e.g. skiing, off-road driving).

Different types of ecosystems have differing values in terms of resources for humans. Not all types of ecosystem have undergone the same amount of habitat destruction. Some habitats have only been slightly modified on a global scale such as deserts, which do not provide a particularly good place to grow crops and pose difficulties for human survival and urbanisation. Rainforests, on the other hand, have been disappearing at a huge rate since the beginning of the 20th century. In Australia 75% of rainforest habitat has been lost. Habitat destruction often occurs in the same areas as high levels of biodiversity.

Biodiversity hotspots

A **biodiversity hotspot** is a region that hosts a large amount of biodiversity and also experiences a lot of habitat destruction. These areas have high concentrations of **endemic** species found nowhere else in the world and which are under serious threat from extinction due to loss of habitat.

Ecologist Norman Myers worked on creating a list of biodiversity hotspots that met certain criteria. Myers identified 25 biodiversity hotspots around the world that are undergoing substantial habitat destruction. Today 36 global hot spots have been recognised as meeting Myer's definitions (Figure 13.1.1). To qualify as a biodiversity hotspot a region must contain at least 0.5% of the world's plant species as endemic and must have lost 70% or more of its original habitat. Historically these hotspots covered 12% of Earth's land but today their undamaged habitat covers less than 2% of the land. This tiny percentage of land area is home to a huge number of species: 50% of the world's plant species and 42% of the land vertebrate species.

Two biodiversity hotspots have been identified in Australia: Kwongan (south-west Australia) and the forests of east Australia.

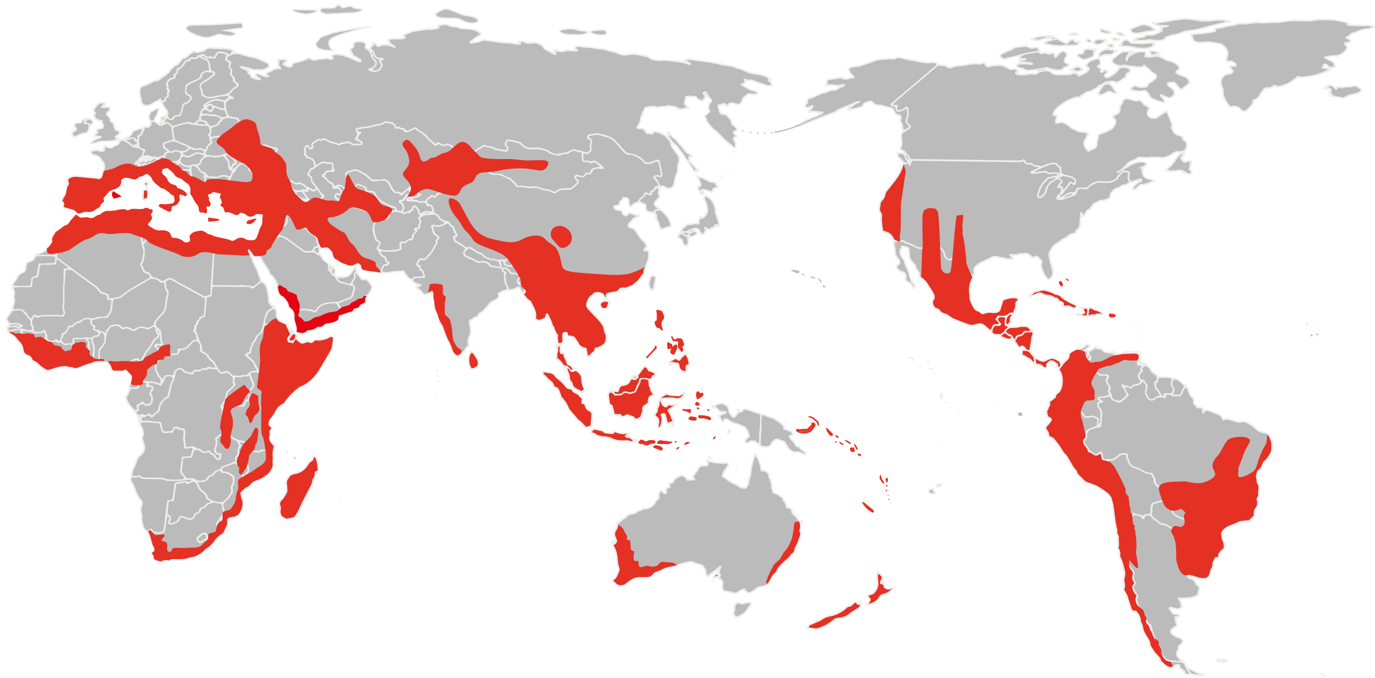


FIGURE 13.1.1 Earth's terrestrial biodiversity hotspots (in red). Biodiversity hotspots cover a small fraction of Earth but are home to a large number of species.

Habitats can be lost by complete destruction where one habitat is converted to a completely different sort. Take, for example, a forest knocked down to clear land for farming or the development of housing. The forest that contained **ecological niches** for an array of species is replaced by buildings or simple pastures, which cannot support species that rely on trees. Species are likely to become extinct if they are destroyed in the deforestation process or if they cannot reach a new forest habitat.

Habitat fragmentation

Another way that loss and change of habitat can cause extinction is through **habitat fragmentation**. Habitat might not be destroyed completely but an area of habitat that was once large and continuous is broken up into smaller patches with dissimilar habitat in between. This changes the amount of habitat available and the spatial distribution of the habitat, which leads to reduced connectivity throughout the habitat.

Habitat fragmentation can cause local extinction for a number of reasons.

Smaller population sizes

Fragmentation of habitat generally isolates a once large population into smaller populations that cannot breed with each other. An isolated population might only contain a subset of the genes of the original population. These genes cannot be replenished as migration and **gene flow** is restricted by the new habitat that has divided up the old habitat. **Inbreeding** can occur and the population is likely to become extinct.

Lack of habitat between fragments

Some species are area sensitive, and may need to forage or hunt over very large areas using multiple fragments. Travelling between fragments can cause mortality as fragmented habitat is often divided up by dangerous areas like roads.

The bare-nosed (common) wombat (Figure 13.1.2) has a home range of up to 27 ha. When travelling on highways through eastern New South Wales and Victoria, it is very likely that you will spot a wombat that has become roadkill. The large home range of wombats means they might not have enough continuous habitat to use without having to cross roads.

FIGURE 13.1.2 The common wombat (*Vombatus ursinus*) grazing on a lawn

Edge effects

When habitat is fragmented, an abrupt boundary occurs between the existing and altered habitat. When a large area of habitat is divided up into smaller patches, boundary areas increase and more edges exist. The edges of a habitat have different species compositions and abiotic factors than the middle of a habitat. The edges of forests often have higher temperatures and lower soil moisture and humidity than the middle of a forest. If the forest becomes fragmented into patches, the habitat will have more areas with high temperatures and low humidity than before. Plants that need lower temperatures and high soil moisture and humidity will be less likely to survive. The distance between the edge and middle of a patch also decreases with habitat fragmentation. Edges that have been created by human activities are also more abrupt than natural habitat edges, which normally display a more gradual change between habitats.

INVASIVE SPECIES

Invasive species have caused extensive biodiversity loss worldwide. The success of invasive species is often due to their association with humans. Species have been introduced to new areas by humans either accidentally or deliberately, and the movement of humans across the globe has enabled species to establish in areas they would not normally reach. Invasive species include pests, weeds, disease and parasites.

Impacts of invasive species

Invasive species can cause declines in native populations through a range of direct and indirect interactions.

Predation and herbivory

The greatest cause of native extinction by invasive species is from the introduction of new predators or herbivores. When a species has evolved in the absence of another, it is unlikely to have defence mechanisms to combat predation or herbivory by the new species.

In Australia 30 mammal species have become Extinct since the arrival of European humans and animals. Introduced cats and foxes have contributed to at least 20 of these extinctions and still pose threats to the small- and medium-sized mammals that exist in Australia today such as species of bandicoots, wallabies and native rodents. Foxes hunt animals up to 5.5 kg and cats prefer prey under 2 kg. Australia's mammals are very vulnerable to predation from cats and foxes due to having evolved without the presence of feline or canine mammalian predators—with the exception of the dingo, which has only existed in Australia for around 4000 years. The dingo has not had the same impact as cats and foxes, perhaps because its numbers have always been comparatively low and because it favours different prey and hunting techniques. Feral cat numbers are estimated to be up to 18 million and each cat is capable of catching up to 30 prey each night. Cats and foxes face few predators in Australia and their population numbers have gone uncontrolled for a long time. Foxes and cats are both generalist hunters and vary their diet depending on the availability of prey. When rabbits are plentiful they are favoured for prey.

FIGURE 13.1.3 Two species of camel (*Camelus dromedarius* and *Camelus bactrianus*) are invasive species in Australia. They cause significant land degradation and strip native vegetation.

Introduced herbivores such as camels (Figure 13.1.3) and rabbits can cause significant land degradation and pose problems for Australian wildlife. Control regimes to limit rabbit numbers can cause diet shift in foxes and cats, resulting in higher predation of native mammals. Native mammals are especially at risk in areas where fire regimes are poor and agriculture has degraded their natural habitat. In these areas ground cover is removed and there are fewer places for native mammals to shelter and hide, making predation much easier for cats and foxes.

Poison baiting, shooting and trapping programs have been set up all over Australia to attempt to reduce feral fox and cat numbers but populations are so large and widespread that it is a very difficult and costly task. Research suggests that dingoes might be useful in controlling fox and cat numbers. Dingoes can pose a threat to livestock so populations have mostly been removed or heavily controlled in agricultural areas. In places where dingo populations still exist, cat and fox numbers are lower. It has been shown that the dingo preys on these invasive species and the presence of dingoes also limits the hours that cats spend hunting. Cats come out much later at night when the dingoes are less active. Native mammal species are also less active during this time, decreasing their chance of being discovered and eaten by a cat.

Habitat modification

The presence of an invasive species can cause modification of an entire habitat and threaten the existence of native species that require a particular environment for survival. The behaviour of an invasive species can strongly affect the native organisms in the area it invades, changing species abundance and distribution. An invasion can make a habitat more uniform and remove a complex arrangement of microhabitats. For example, beavers from North America were introduced to Argentina in the 1940s to begin a fur trade (Figure 13.1.4). The beaver population started with only 50 or so individuals but a lack of predators and competitors and plentiful resources for beavers caused rapid population growth and widespread distribution. Invasive beavers in Argentina are causing modification of forest and stream habitats where they rapidly chew down trees to create dams. The tree species in Argentina are not able to grow back once chewed down to roots, unlike the species found in North America. Beavers also modify the shape and structure of streams, which has a great impact on the water cycle. Beavers have converted millions of acres of standing forest to logged areas and turned many streams into boggy wetlands. Native species that live in forests and flowing fresh water have been displaced. This habitat change can also facilitate the spread of other introduced species that take advantage of the grassland habitats where native forests are unable to regenerate.

FIGURE 13.1.4 American beaver (*Castor canadensis*) in Tierra del Fuego, Argentina, South America

Competition

Invasive species can create new competitive interactions with native species for food and space. An invasive species might occupy a similar niche to a native species requiring the same habitat and resources. According to the **competitive exclusion principle** two species cannot coexist if they use the same resources in the same way and eventually one species will out-compete the other. Invasive species may be strong competitors against natives and cause native extinction if they are dominating resources. In the UK introduced grey squirrels from North America have a competitive advantage over the native red squirrels of Europe. Both species of squirrel feed on acorns but the grey squirrel has a tolerance to chemicals found in unripe acorns. This means grey squirrels can eat unripe and mature acorns but red squirrels can only eat ripe acorns, as they find the unripe ones unpalatable. Grey squirrels get to the food resource of acorns first, eating them in the unripe stage which limits the number of acorns that can ripen and become available to the red squirrels. Red squirrels may be prevented from reproducing if they cannot gain enough food. Their population numbers are declining while grey squirrels become more abundant (Figure 13.1.5).

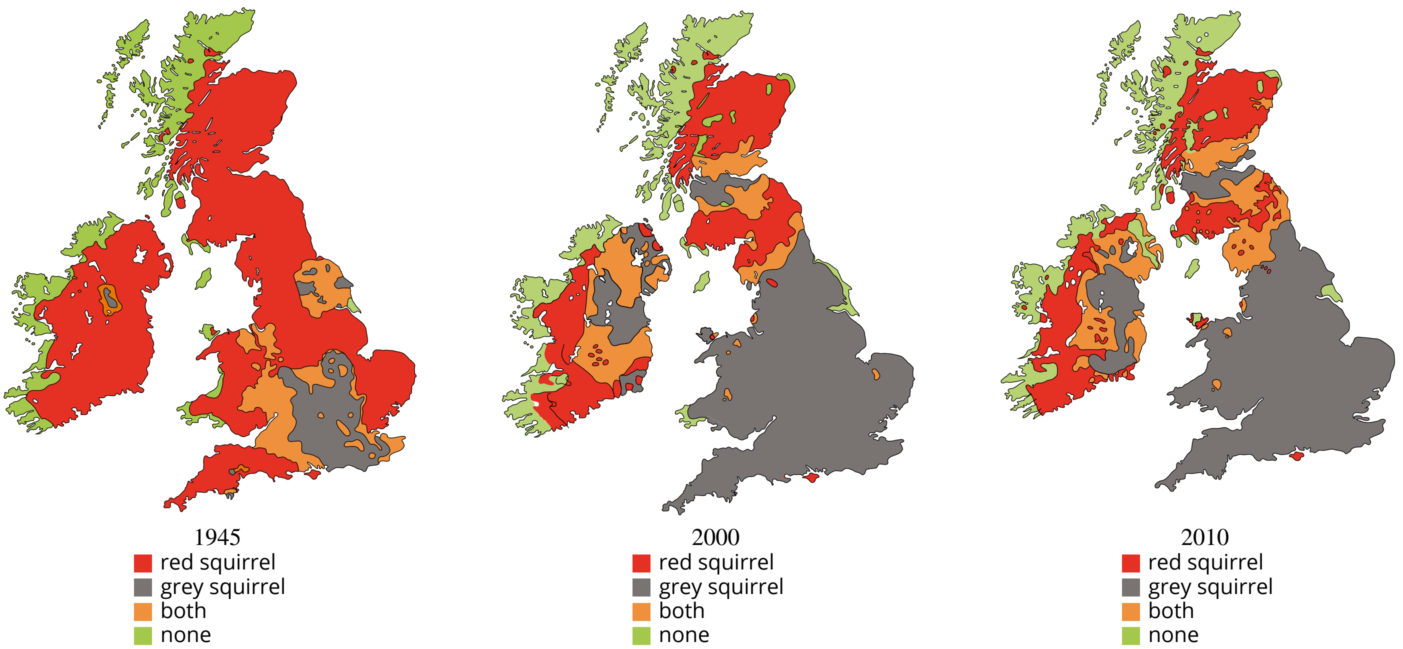


FIGURE 13.1.5 Changes in red squirrel distribution across the UK and Ireland between 1945 and 2010

Characteristics of successful invaders

Many invasive species have established populations and become successful invaders in Australian ecosystems. Most of these invasive species arrived with European colonisation. Some species were brought over intentionally to be used for hunting or agriculture, such as foxes, rabbits, goats and cats (Figure 13.1.6), while others were accidentally introduced, such as rats and house mice. Many of these species have characteristics that allow them to readily adapt and survive in new environments.

Examining a range of ecosystems that have become invaded and the types of species which invade successfully reveals common traits of susceptible ecosystems and successful invaders.

Few enemies

When a species arrives somewhere outside of its natural range it may escape its natural enemies. A predator or competitor that existed in its natural environment is unlikely to exist in its new environment. The introduced species can quickly become invasive because its population numbers are not controlled. For example, a plant species may become invasive in a new environment if no herbivores exist in that ecosystem to limit its population growth.

FIGURE 13.1.6 Feral cats (*Felis catus*), one of the most successful invasive species in Australia

Rapid growth, maturation and reproduction

Species that grow, mature and reproduce quickly are more likely to be successful invaders. Producing large numbers of offspring allows populations to grow and spread quickly. Covering large areas of habitat in large numbers helps to ensure the species' persistence even if mortality is high within its populations.

Human association

Species that are often associated with humans are likely to reach new environments outside their natural habitats. This can happen intentionally where people deliberately bring organisms into a new ecosystem for hunting, agriculture or aesthetic reasons. It may also occur unintentionally where a species is unknowingly introduced. Animals such as rats and mice have become successful on nearly every continent on Earth. They often stowed away on ships and could survive the journey then thrive once they reached new environments.

Adaptability

Generalist species can tolerate a range of environments and food sources, making them very adaptable to new environmental conditions. Having a varied diet contributes to the success of a species outside its natural range; species with specialised diets (**specialists**) are not likely to become successful invaders as their specific food source might not be found in a new environment. Koalas are an example of a specialist species, as they only eat *Eucalyptus* leaves and would therefore not survive anywhere outside the range of particular species of *Eucalyptus*. Invasive plants are often generalists and can tolerate various temperatures and soil conditions. Generalist plants that do not require specific pollinators or seed dispersers may be able to improve their reproductive success in their new environment by attracting and utilising the local animals as pollinators and seed dispersers.

Feral cats (*Felis catus*) are one of the most successful invasive species in Australia. They have many of the characteristics of successful invaders: no natural predators in Australia, rapid growth and reproduction, a close association with humans and have adapted to a range of environments. Feral cats now pose one of the greatest threats to Australia's native wildlife.

FIGURE 13.1.7 The Blue Mountain Swamps in the Sydney Basin Bioregion, New South Wales, is listed as a vulnerable ecological community. The ecological community is threatened by erosion, sedimentation and weed invasion.

Characteristics of vulnerable ecosystems

Some ecosystems are more likely to be susceptible to invasive species than others (Figure 13.1.7). Ecosystems that are most readily invaded often share common characteristics. Usually the ecosystem has 'space' for the invader; this may be because a disturbance event has left a niche unoccupied or because the niche was never occupied. An invader is also likely to be successful if the new ecosystem is similar to its native ecosystem.

Disturbed ecosystems

A recently disturbed or degraded ecosystem has a higher likelihood of being invaded than a stable ecosystem. Invasive species may be able to become established in a new ecosystem if disturbance has weakened species interactions and the population numbers of native species. In Chapter 12 you learnt about New South Wales sea urchins invading south-eastern Australian waters as an example of two different disturbances allowing for invasive success. The warming currents have allowed the sea urchin to expand its range. This plus the reduction in numbers of rock lobsters, the sea urchins' natural predator, have contributed to the invasion and establishment of sea urchins in kelp forest ecosystems.

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Niche and resource availability

Invasive species are successful in ecosystems with high resource availability and unoccupied niches. If resources are more plentiful in a new ecosystem the introduced species may be able to grow faster and reproduce better than in its natural ecosystem. A new species in an ecosystem might also be able to take advantage of unoccupied niches without being limited by competition.

Moderate climate

Ecosystems in extreme climates are less likely to be invaded than ecosystems in moderate climates. Moderate climates are more likely to be within the range of survival for most species. The extreme environment of Antarctica means few introduced species have managed to survive and establish in the cold climate. The opposite is true for temperate and tropical climates where many invasions occur. However, as climate change warms Earth and more tourists are reaching Antarctica, invasive species may become more of a problem in this region.

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The cane toad invasion

The cane toad (*Rhinella marina*) (Figure 13.1.8) was introduced to Australia in the 1930s to try to control the native species of beetle that was causing destruction of sugar cane crops in Queensland. A few hundred cane toads were initially released in northern Queensland but did not seem to have any effect on the beetle populations. Now with a population of over 200 million, the range of cane toads has expanded to the Northern Territory and New South Wales, with its expansion in the west estimated at up to 60 km each year. The cane toad is poisonous and produces toxins that can kill Australian predatory animals, which have not adapted to the toxin as it does not occur in native frogs and toads. The cane toad has not caused any species-wide extinctions but has contributed to declines in populations of goannas, snakes, crocodiles and quolls that may prey on the toads. Studies conducted in Kakadu National Park demonstrate local extinctions of the northern quoll (*Dasyurus hallucatus*) since cane toad invasion. At two sites where cane toads arrived quoll populations have entirely disappeared and 31% of quoll deaths could be attributed to lethal ingestion of cane toad toxins. The quoll population remains stable at another site that did not see the arrival of cane toads.

Some native species have adapted through evolutionary selection to avoid or tolerate cane toad poisons or learnt to avoid the toads altogether. If an animal consumes a small, non-lethal amount of toxin, it will experience poisoning and feel very unwell but it will not die and the animal may learn to avoid cane toads in the future. Scientist Richard Shine found that the northern quoll could successfully be conditioned to avoid cane toad poisoning through taste aversion. He created a population of ‘smart’ quolls by feeding juveniles dead toads containing a nausea-inducing chemical. This ‘smart’ quoll population and another ‘naive’ quoll population (that had not undergone the taste aversion conditioning) were released into an area populated by cane toads. He found that the smart quolls had higher survival rates than the naive quolls and were less likely to prey on cane toads.

FIGURE 13.1.8 Cane toad (*Rhinella marina*) in Shoal Bay, NSW

OVEREXPLOITATION

Overexploitation has caused many species to become Extinct. Harvesting some species for food or products can remove individuals from a population faster than they can reproduce. European colonisation saw the exploitation of species on most continents. Previously abundant, large or edible species were harvested to extinction. A classic example is the case of the passenger pigeon, which numbered in the billions at the beginning of the 1800s and was the most numerous bird in North America. By 1900 none survived in the wild and they had been hunted to extinction.

An increasing human population, shrinking habitats and advances in technology mean that harvesting most wild populations is no longer sustainable, yet harvesting of these populations still continues. Unfortunately, as a species disappears demand for the species increases because products derived from the species become rarer and more expensive. Many mammalian species have suffered from exploitation where they have been hunted for fur, horns or antlers, or trapped and traded as exotic pets. As exploited animals become rarer, more restrictions have been placed on hunting these populations and trading animal products. This has created a black market and caused illegal poaching in reserves and protected areas, further depleting population numbers.

Overexploitation greatly affects marine plants and animals where large, commercial fishing operations occur on a global scale and exploit over 400 species. An estimated 90% of all fish stocks are overexploited, depleted, fully exploited or in recovery from exploitation. Some fishing techniques also lead to a decline in non-target marine species. Seabirds, turtles and marine mammals can get caught in nets and lines intended to catch fish and edible crustaceans.

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Totems help prevent overexploitation

In Indigenous cultures throughout Australia totems define people's roles and relationships to each other and the natural world. Every individual is associated with totemic ancestors of the Dreaming. Some totems are inherited and represent nation, clan and family groups. Every person also has a personal totem. Totems include plant and animal species as well as environmental factors like water and fire. People believe their totems are protective. For example, the family totem of the Monaro Ngarigo people is the 'Doonooch' or night owl. They believe the owl protects them, and will become immediately aware of their surroundings at the sight of an owl.

People with a particular totem are required to learn about that totem and pass on their knowledge to others. The inherited arrangement and allocation of personal totems ensures that all parts of the environment are represented and cared for. An individual is responsible for protecting and conserving their totems and must be referred to for all consideration of that totem. For example, red kangaroo people hold particular knowledge about the species and may prevent the killing of red kangaroos for food for a certain time if they believe it needs protection (Figure 13.1.9). People associated with fire totems understand important burning regimes and know when and how to perform burns that will improve the ecological health of an area. Totems help to restrict exploitation of certain resources and promote growth and sustainable use.

FIGURE 13.1.9 Totems, such as the red kangaroo, are an important connection between Indigenous Australians and the land.

POLLUTION

Pollution of the environment is another anthropogenic driver of species extinction and declines in biodiversity. Chemical and physical changes caused by pollutants can affect nutrient cycles and cause changes in environments and ecosystems. Pollutants released by human activities are present in terrestrial and aquatic environments as well as the atmosphere.

With improved technology, chemical production increased 400 times from 1930 to 2000 causing abnormal levels of naturally occurring chemicals and synthesis of new chemicals. Fertilisers have been used to increase crop productions to keep up with a growing human population and more mouths to feed. Fertilisers are applied to agricultural land and contain naturally occurring minerals like nitrogen, phosphorous and potassium. Only some of the fertiliser is taken up by plants; the rest accumulates in soil, leaches into the groundwater or ends up as run-off in surface waters where it can reach streams, rivers, lakes and oceans. Fertiliser run-off brings new nutrients into waterways and can cause **eutrophication** (Figure 13.1.10), where excess nutrients in the water allow an overgrowth of plankton and algae. Algal blooms take over where they flourish using high levels of phosphates and nitrates but eventually, when these chemicals run out, the algae dies and decomposers flourish. Large numbers of decomposers mean they use up most of the available oxygen in the water and species that require oxygen-rich waters die. This process can cause dead zones where algae and decomposers persist and all other species in an ecosystem are lost.

FIGURE 13.1.10 Eutrophication caused by coastal run-off from agricultural areas in Tasmania

Litter and plastics pollute water and cause mortality among many aquatic species. Around 300 million tonnes of plastic is produced each year worldwide, a huge number that is continually increasing; 10–20 million tonnes of that plastic end up in the oceans. Most plastics take hundreds of years to break down and plastic floats so it does not all just sink to the bottom of the sea floor. The Great Pacific Garbage Patch was discovered in 1997 and is a huge accumulation of plastic. The extent of the patch is large, possibly about the size of Australia but estimates are difficult as the plastic is suspended in water. It is mostly composed of small plastic particles in the top 10 m of the water, with some larger plastic objects floating around as well. There is six times more plastic than zooplankton in this area.

Small plastic particles can enter food webs, where they are taken up by zooplankton and transferred to higher trophic levels. Many large species mistakenly ingest plastic as well. It is easy to see how a plastic bag in the water could look like a jellyfish or other edible sea creature. Autopsies performed on sea life often reveal a lot of plastic in the stomach contents that can prevent the organism from feeding properly (Figure 13.1.11).

FIGURE 13.1.11 Dead black-footed albatross (*Phoebastria nigripes*) showing the plastic it has ingested while feeding at sea. Photographed at Midway Atoll, USA.

Pollution of the air and atmosphere also occurs from human activities, affecting species all over the world. Many chemicals that are used in air conditioners, pesticides and aerosols destroy the ozone layer in the upper atmosphere. The ozone forms a protective layer that restricts harmful wavelengths from reaching Earth. When ozone is depleted it lets more UV-B rays reach Earth's surface. B radiation can inhibit reproduction of single-celled organisms like algae and phytoplankton that support food webs of many species. Reduction in these producer populations could cause collapses and extinction in a huge amount of consumer species.

Acid rain is caused by pollution in the air and can have negative effects on aquatic and terrestrial ecosystems. When burning fossil fuels sulfur dioxide and oxidised nitrogen are released, which form acids in the atmosphere. When it comes back down to Earth as rain, it sinks into the soil and ends up in lakes, streams and oceans. Acidic water absorbs more aluminium than water with neutral pH levels. Low pH and high levels of aluminium are harmful to many fish and aquatic invertebrates. It can kill them directly or disrupt reproduction (e.g. prevent eggs from hatching).

Low pH levels in soils also kill important microbes, and chemicals needed by plants are leached away from roots. Acidic soils also allow mobilisation of toxins like aluminium, making it difficult for plants to take up water. Acid rain can also cause physical damage to plants, leaves and other structures, impeding photosynthesis and reproduction.

CLIMATE CHANGE

Human activities that cause pollution also drive climate change. Burning fossil fuels and some agricultural practices produce greenhouse gases that are released into the atmosphere. Greenhouse gas emissions cause an overall surface warming effect on the planet which in turn changes water systems and patterns of extreme weather. The cumulative effect of climate change place selection pressures on species all over the world.

Most species are adapted to a particular temperature range, and temperature change in their natural habitat may mean that habitat is no longer suitable. Some species can migrate and move to areas with appropriate temperatures as global averages increase. Other species that require extremely cool temperatures or are found in already warm environments are threatened with extinction.

Global warming can have direct impacts on species reproduction. Many species of reptiles lay eggs whose sex is determined by incubation temperature. For example, the New Zealand tuatara (Figure 13.1.12), the only living reptile of the Sphenodontidae family, is experiencing a change in sex ratios throughout the population where males are outnumbering females. Studies have shown that incubating eggs at higher temperatures (above 22°C) produces males, while lower temperatures (under 21°C) produce females. As global temperatures increase, the tuatara population could eventually lose its females and the species would no longer be able to reproduce.

FIGURE 13.1.12 New Zealand reptile, tuatara (*Sphenodon punctatus*)

FIGURE 13.1.13 The recently Extinct Bramble Cay melomys (*Melomys rubicola*)

Shifts in temperature also cause shifts in water. Warm temperatures are causing sea ice to melt which means there is more water in the ocean and sea levels are rising. Thermal expansion also adds to sea level rise where increased ocean temperatures mean the water expands and takes up more space. Low-lying coastal areas are most affected where sea level rise may destroy those habitats. The first mammalian extinction directly related to global warming and sea level rise occurred in 2016. The Bramble Cay melomys (*Melomys rubicola*) (Figure 13.1.13) was a small rodent endemic to the Great Barrier Reef. Sea level rise occurred at 6 mm per year between 1993 and 2010 in the region which is twice the global average. This species of melomys lived on a small coral reef and the cause of extinction seems to have been from ocean inundation and a higher incidence of storms causing habitat loss and possibly direct mortality of individuals.

13.1 Review

SUMMARY

- Human activities can cause extinction and biodiversity loss through habitat destruction, invasive species, overexploitation, pollution and climate change.
- Habitat destruction reduces available habitat for many species and habitat fragmentation isolates populations and creates edge effects.
- Invasive species can cause extinction of native species through new predation and herbivory interactions, modifying habitat and outcompeting natives.
- Invasive species often share the following common traits:
  - few enemies (predators or competitors)
  - rapid growth, maturation and reproduction
  - human association
  - adaptability.
- Ecosystems vulnerable to invasion often share the following common traits:
  - disturbed ecosystems
  - niche and resource availability
  - moderate climate.
- Overexploitation causes extinction when a population is harvested at unsustainable levels.
- Pollution from human activities causes chemical changes in the air, soil and water.
- Climate change causes a global warming effect, changes sea levels and modifies extreme weather patterns.
- All these factors often act together as strong selection pressure and species become Extinct.

KEY QUESTIONS

1 List five activities that result in habitat destruction.

2 Give an example of an invasive species in Australia. Describe its effect on native species.

3 List four common characteristics that contribute to the success of invasive species.

4 List three common characteristics of ecosystems vulnerable to invasion.

5 Why do exploited populations sometimes become further exploited when their population numbers are small?

6 What is eutrophication and how does it change an ecosystem?

7 How might climate change cause species extinction? Provide an example.

8 What is meant by the 'base rate' of extinction?

9 List three causes of mass extinction events.

10 What criteria must a region meet to be classified as a biodiversity hotspot?

11 Do you think more areas of the world will become classified as biodiversity hotspots in the future? Explain your reasoning.

13.2 Predicting impacts on biodiversity

Reflecting on past extinction events and ecosystem changes helps to inform us about the ways we might expect future changes in the environment to affect biodiversity. Predicting these changes and their effects allows us to take action to prevent population declines and extinctions before they occur. Species will have a much better chance of survival if we understand the way they react to certain environmental changes and if we can mitigate those changes.

MONITORING

To understand how a species is affected by changing environmental conditions, we need to examine the environment and the species itself. **Monitoring** is the process of researching and gathering information on some sort of variable; for example, population size of an endangered species, forest cover or water quality. Monitoring is used to assess the state of a system or population and record changes over time, allowing us to infer and understand reasons for those changes. Monitoring is useful for extracting information at any range of spatial or time scales. It is possible to monitor global temperatures from many thousands of years ago up until the present day or we can monitor the daily growth and distribution of microbes on an agar plate. Sampling of biotic and abiotic components of an ecosystem allows conclusions to be made about the condition of that ecosystem.

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Monitoring water quality

Monitoring is carried out across the water supply system to understand and manage the quality of water that eventually ends up as drinking water in our taps. In the Sydney area, Sydney Water and WaterNSW have set up a monitoring program to assess water quality in catchment streams, rivers, reservoirs, the bulk water distribution system, and at water filtration plants. WaterNSW conducts routine, targeted, investigative and event-based monitoring of key water quality parameters at various locations.

Sampling teams collect samples and data at multiple locations. One sampling method is to use a multi-probe water quality instrument (Figure 13.2.1a), which gives immediate water quality data. Water samples are also taken using a hydrobiodepth sampling bottle and winch to collect water for lab analysis. Another measure of water quality is light penetration. Light penetration gives an indicator of how cloudy the water is (turbidity) and can be measured using a device called a Secchi disc (Figure 13.2.1b). The disc is lowered into the water until the pattern on it is no longer visible, indicating how turbid (cloudy) the water is. Water quality testing instruments can be connected to dataloggers so that measures of water quality taken in the field can be directly sent to the laboratory and stored for later analysis (Figure 13.2.1c).

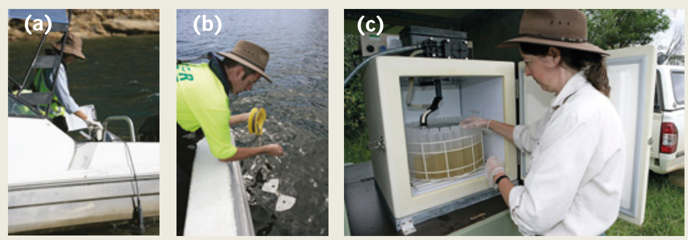

FIGURE 13.2.1 Sydney Water and WaterNSW monitor water quality using a variety of methods. Water samples can be collected in the field and sent to the laboratory for testing or testing can be done while in the field. (a) Probes can collect data directly from water bodies. (b) A Secchi disc is used to measure light penetration, giving an indication of turbidity (how cloudy the water is). (c) Sampling stations can be connected to dataloggers to retrieve and store water quality data in the field.

A range of basic parameters are monitored to assess water quality, including:

- physico-chemical factors (e.g. pH, electrical conductivity, turbidity)
- biological factors (e.g. algal species and numbers)
- organics (e.g. organic carbon, pesticides and herbicides)
- nutrients (e.g. total and dissolved oxygen)
- metals (e.g. iron and manganese)
- pathogens (e.g. bacteria, *Cryptosporidium*, *Giardia*)
- aquatic macroinvertebrates.

This monitoring data is used to identify water quality trends over time and allows for identification and mapping of any contaminants in the water and their potential impact.

Source: WaterNSW

Bioindicators

Bioindicators are useful species for monitoring changes within an ecosystem. They are species that reflect a particular environmental condition. It is often easier to examine theses indicator species than to examine the environmental condition, or set of conditions, which can involve measuring many different parameters. Measuring the dynamics of a single population of indicator species is a relatively cost-effective and reliable way to detect ecosystem change. The presence, absence or abundance of a bioindicator demonstrates a distinctive aspect of the environment. A physical change or change in the behaviour of indicator species can also reflect a change in the environment. The types of organisms that make good indicators are species that are sensitive to change and react consistently to environmental shifts. They must be representative of the other organisms in the ecosystem, by quickly reflecting stress events that cause harm to other species and the ecosystem as a whole. Bioindicator species should also be easy to observe and sample.

Lichens

Lichens are often used as bioindicators because they are very sensitive to air pollution (Figure 13.2.2). Lichens are a group of composite organisms made up of algae or photosynthetic bacteria and fungi in a **symbiotic** relationship. Lichens occur in many terrestrial environments and can grow on almost any substrate. This is because they do not rely on ground roots for nutrient transfer but instead obtain all nutrients from direct exposure to the atmosphere and rainwater. The do not have a cuticle and have a high surface area to volume ratio. These characteristics mean lichens are unable to avoid accumulation of atmospheric toxins making them useful in assessing air pollution, ozone depletion and metal contamination. The types of lichen/species composition found in an ecosystem indicate levels of air pollution. Presence and abundance of leafy, hairy or branching lichen growth forms indicate clean, non-polluted air. The most tolerant lichens have a crusty growth type and indicate some air pollution. Where no lichens are present, air is likely to be heavily polluted with sulfur dioxide.

FIGURE 13.2.2 Large leafy lichens growing on a fence post, indicating low levels of air pollution

Macroinvertebrates

Macroinvertebrates are invertebrates (animals without a backbone) that can be seen with the naked eye (Figure 13.2.3). Aquatic macroinvertebrates include a range of species that spend some or all of their life stages in water. Freshwater macroinvertebrates can be used to determine the water quality of lakes, streams and rivers. Different species of these macroinvertebrates have different tolerances or sensitivities to variables associated with pollution. Some species can survive in high levels of salinity, turbidity or nutrients or in poorly oxygenated waters, while other species cannot. Examining the diversity and abundance of different macroinvertebrates in a system provides an indication of the condition of the water at a particular site. Sampling and comparison across different sites can reflect contamination from anthropogenic processes, such as run-off from agriculture, occurring near waterways (Figure 13.2.4).

FIGURE 13.2.3 Stonefly larva are sensitive to water pollution and are usually found in cool, clean streams with high levels of dissolved oxygen. Their sensitivity to pollution make stonefly larvae valuable bioindicators.

FIGURE 13.2.4 Students sampling stream macroinvertebrates using a kick-seine net. Macroinvertebrates are important bioindicators of water quality.

Worked example 13.2.1 CCT N S

ESTIMATING WATER QUALITY: STREAM POLLUTION INDEX (SPI)

A sample of aquatic macroinvertebrates was taken at a stream site in New South Wales farmland. A total of 80 specimens were collected: 3 stonefly nymphs, 12 water mites, 6 whirligigs, 3 yabbies, 1 nematode, 12 midge larvae, 2 damselfly nymphs, 10 water boatmen, 9 freshwater slaters, 13 mosquito larvae and 9 freshwater snails. This data is presented in Table 13.2.1. A weight is given to each row of data which can be determined from the weight factor table (Table 13.2.2). Using this data the water quality can be estimated by calculating the Stream Pollution Index (SPI). The SPI score indicates the water quality at the stream site (Table 13.2.3).

TABLE 13.2.1 Water quality data collected from a NSW stream

	A	B	C	D
Macroinvertebrate type	**Sensitivity rating**	**Number of macroinvertebrate type**	**Weight factor**	**Sensitivity rating × weight factor**
stonefly nymphs	10	3	2	20
water mites	6	12	4	24
whirligigs	4	6	3	12
yabbies	4	3	2	8
nematode	3	1	1	3
midge larvae	3	12	4	12
damselfly nymphs	3	2	1	3
water boatmen	2	10	3	6
freshwater slaters	2	9	3	6
mosquito larva	1	13	4	4
freshwater snails	1	9	3	3
	Total	80	**30**	**101**

SPI = sensitivity rating x weight factor total/weight factor total = 101/30 = 3.367

Estimate the water quality of the stream by calculating the Stream Pollution Index (SPI)	
Thinking	**Working**
Identify each macroinvertebrate type that was collected.	Record each macroinvertebrate type collected in the first column of the table.
Identify the 'sensitivity rating' for each macroinvertebrate.	Refer to Table 13.2.4. Record the 'sensitivity rating' for each macroinvertebrate into column A.
Identify the number of each macroinvertebrate type collected.	Record the number of each macroinvertebrate type collected in column B.
Calculate total number of macroinvertebrates.	Add up the number of each macroinvertebrate type in column B. Enter the total value in the last cell of column B. Total number of macroinvertebrates = 80
Identify the 'weight factor' for each macroinvertebrate.	Refer to Table 13.2.2. Record the 'weight factor' for each macroinvertebrate in column C.
Calculate the 'sensitivity rating × weight factor'.	Multiply the 'sensitivity rating' values (column A) by the 'weight factor' values (column C). Enter this data into column D.
Calculate the total 'weight factor'.	Add up the 'weight factor' values (column C). Enter the total value in the last cell of column C. Total weight factor = 30
Calculate the total 'sensitivity rating × weight factor'.	Add up the 'sensitivity rating × weight factor' values (column D). Enter the total value in the last cell of column D. Total sensitivity rating × weight factor = 101
Calculate the Stream Pollution Index (SPI).	Divide the total 'sensitivity rating × weight factor' (column D) by the total 'weight factor' (column C). $\text{SPI} = \frac{\text{sensitivity rating} \times \text{weight factor total}}{\text{weight factor total}}$ $\text{SPI} = \frac{101}{30}$ SPI = 3.367
What does the SPI score indicate about the water quality of the stream?	Refer to Table 13.2.3. An SPI score of 3.367 indicates the stream has a 'fair' water quality rating; there may be some pollution and lower levels of dissolved oxygen at the site.

TABLE 13.2.2 Weight factor assigned to macroinvertebrate types based on abundance

Number of each type found	Weight factor
1 to 2	1
3 to 5	2
6 to 10	3
11 to 20	4
20+	5

TABLE 13.2.3 SPI score and water quality ratings

SPI score	Water quality rating
under 3	poor
3 to 4	fair
4 to 6	good
above 6	excellent

In statistics, weight factors assign heavier (more) or lighter (less) importance to data points. Weight factors are used to help correct disproportionate sampling. In biodiversity and abundance surveys, a weight factor is derived for each type of organism.

Worked example: Try yourself 13.2.1

ESTIMATING WATER QUALITY: STREAM POLLUTION INDEX (SPI)

Macroinvertebrates were collected at another site from the same stream. This site was further upstream in a national park. The following macroinvertebrates were collected: 4 stonefly nymphs, 2 mayflies, 12 caddisfly larvae, 1 alderfly larvae, 4 rifle beetles, 16 water mites, 6 yabbies, 10 dragonfly nymphs, 2 whirligigs, 4 water striders, 3 nematodes and 1 freshwater snail. Follow the worked example above to complete the table below and work out the SPI score and water quality rating of this stream site.

	A	B	C	D
Macroinvertebrate type	**Sensitivity rating**	**Number of macroinvertebrate type**	**Weight factor**	**Sensitivity rating × weight factor**
	Total			

SPI = sensitivity rating x weight factor total/weight factor total = / =

Estimate the water quality of the stream by calculating the Stream Pollution Index (SPI)

SKILLBUILDER N S

Using aquatic macroinvertebrates as bioindicators

The water quality of a stream can be examined by collecting and identifying macroinvertebrates. A scoring system from 1 to 10 is used to rate the sensitivity of each type of organism. Species (or groups of species) that are tolerant to pollution and poor water quality receive a low sensitivity rating. Species that require pristine environments have a high sensitivity rating. The sensitivity rating of different species along with their abundances provides a Stream Pollution Index (SPI) for the sampling area. The SPI is used as a scoring system to indicate the level of pollution in a stream or at a stream site. Areas with a high SPI score display low pollution levels and high levels of dissolved oxygen. Table 13.2.4 displays sensitivity ratings of common macroinvertebrates found in New South Wales waterways.

TABLE 13.2.4 Sensitivity rating of common aquatic macroinvertebrates

Sensitivity rating	Type of macroinvertebrate (common names)
10 (highly sensitive)	stonefly nymph
9	mayfly
8	alderfly larva, caddisfly larva
7	rifle beetle
6	water mite
5	beetle larva
4	freshwater yabby, dragonfly nymph, whirligig, water strider
3	damselfly nymph, midge larva and pupa, freshwater mussel, nematode
2	flat worm, diving beetle, water boatman, freshwater slater, hydra
1 (highly tolerant)	leech, mosquito pupa and larva, blood worm, freshwater snail

MODELLING CLIMATE CHANGE

Normally, when scientists want to understand the effect of a particular variable on a system they conduct an experiment where that variable is manipulated in some way. Experimental climate change research is difficult since we do not have a second Earth to experiment on and we cannot easily manipulate climate processes. In order to understand what might happen to Earth when certain climate variables change, mathematical models are used to simulate climate processes and make projections. **Models** are also discussed in Chapter 1.

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Similar models to those used by weather forecasters are used to predict future climate **trends**. Weather models are run at a high spatial resolution focusing on small, specific areas and using the most recent sets of satellite and surface data as the starting point to predict weather events over the following days. Climate models are run at a much larger spatial scale and are used to predict average climate conditions over time rather than the exact weather at a given time on a certain day.

In a global climate model (GCM), Earth is divided up into a three-dimensional grid of cells of about 15 000 km² (Figure 13.2.5). A grid cell is the smallest unit of a model and holds climate-variable information about the land, ocean and atmosphere in that cell. Climate models can be very complex and include many variables. The Global Climate Observing System (GCOS) recognises 50 Essential Climate Variables (ECVs) for global climate modelling (Table 13.2.5). These variables include air temperature, wind speed, atmospheric carbon dioxide, precipitation, sea-surface temperature and vegetation cover.

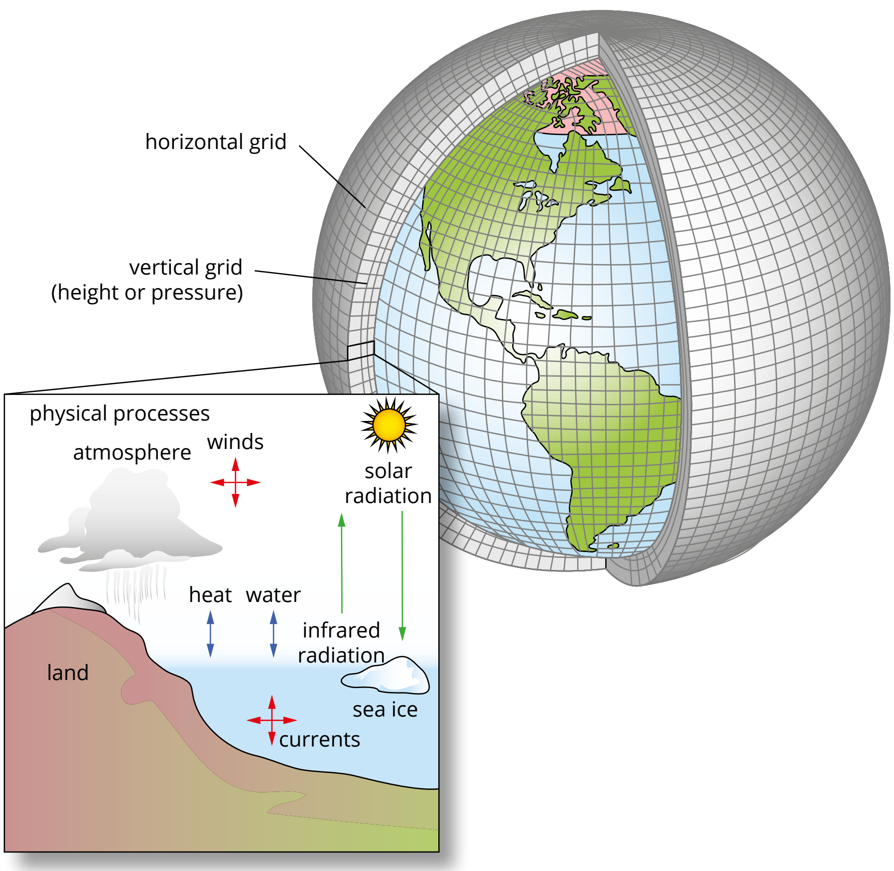


FIGURE 13.2.5 Representation of a global climate model showing the arrangement of grid boxes and processes calculated

Equations are used to simulate change and calculate climate-variable data over a series of time steps. The data given after a single time step are used as the initial state for the next step. Climate models are used to generate simulations of a range of different scenarios and help us to answer questions about what might happen if humans do or do not modify our behaviour about the way we use the Earth.

TABLE 13.2.5 Essential climate variables identified by the Global Climate Observing System

Domain	Essential Climate Variables
atmospheric (over land, sea and ice)	surface: air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget upper air: temperature, wind speed and direction, water vapour, cloud properties, Earth radiation budget (including solar irradiance) composition: carbon dioxide, methane, and other long-lived greenhouse gases, ozone and aerosol, supported by their precursors
oceanic	surface: sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, surface current, ocean colour, carbon dioxide partial pressure, ocean acidity, phytoplankton subsurface: temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers
terrestrial	river discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), above-ground biomass, soil carbon, fire disturbance, soil moisture

BIOLOGY IN ACTION S

Representative Concentration Pathways

Many climate variables are influenced by human activities and must be considered when making projections. The most important variable in terms of global warming is atmospheric greenhouse gas concentration. **Representative Concentration Pathways** (RCPs) are atmospheric greenhouse gas concentration trajectories used for climate modelling research. RCPs provide different concentration scenarios based on assumptions about technology, population growth, and the way we generate energy and use land. There are four RCPs that represent four possible fates of the global climate depending on the amount of greenhouse gases that may be emitted in years to come. The four RCPs are best, intermediate and worst-case scenarios in terms of global warming by 2100 (Figures 13.2.6 and 13.2.7):

1 RCP 8.5—the 'business as usual' scenario where emissions continue to rise throughout the 21st century and lead to high concentrations of greenhouse gases. Under this scenario we assume little is done to mitigate climate change and reduce emissions. Global temperatures would be predicted to rise by 2.6–4.8°C.

2 RCP 6—a stabilisation scenario where greenhouse gas concentrations peak around 2080 then stabilise. This scenario assumes we have taken some actions to reduce emissions and global temperatures would rise by 1.4–3.1°C.

3 RCP 4.5—another stabilisation scenario where greenhouse gas concentrations peak around 2040. This assumes more emission reduction actions have been taken than in the RCP 6 scenario and global warming increases by 1.1–2.6°C.

4 RCP 2.6—a peak and decline scenario where emissions and greenhouse gas concentrations peak by 2020 and then substantially decline. This scenario relies on socio-economic assumptions that strong actions are taken to reduce greenhouse gas emissions. Even so the global temperatures would still be predicted to increase by 0.3–1.7°C.

RCPs are a consistent set of input/starting conditions that can be used by climate scientists for modelling. Using a set of RCPs allows independent modelling studies and research to be compared. If each study used different metrics and assumptions it would be very difficult to compare one study to another. The different scenarios provide a basis for assessing the impact of reducing or not reducing global emissions and concentrations of greenhouses gases.

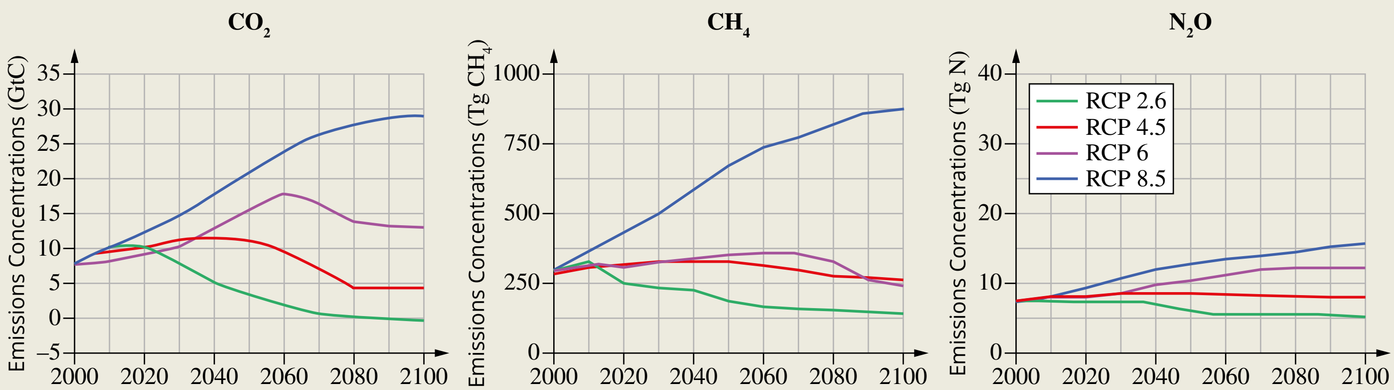


FIGURE 13.2.6 Predicted trends in emissions of three main greenhouse gases under the four RCP scenarios (GtC: gigatonnes of carbon; Tg: teragram (1 trillion grams); CH_4: methane; N: nitrogen)

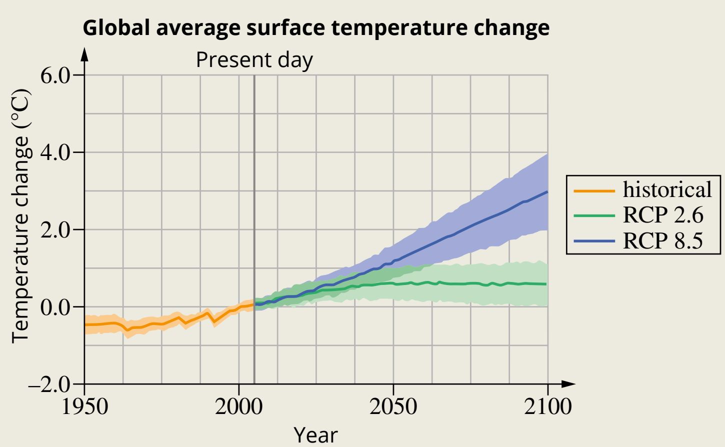


FIGURE 13.2.7 Predicted global average surface temperature change from present day (vertical grey line) to 2100 under the best-case (RCP 2.6, green line) and worst-case (RCP 8.5, blue line) scenarios for global warming mitigation and emission reductions. Historical global average surface temperature (1950–present day) is represented by the yellow line.

SPECIES DISTRIBUTION MODELS

To determine the distribution of a species, scientists record the locations where a species is found. Data can be taken at these locations to understand the ecological niche requirements of a species. For example, records of temperature, rainfall, vegetation type, substrate type, elevation, weather events and the presence or absence of other species provide information about why a species occurs in that area. Once we understand the niche requirements of a species we can determine the conditions that allow a species to survive, grow and reproduce as well as the limits to the conditions it can tolerate. This knowledge can be used along with equations to construct **species distribution models** which predict a species' geographic distribution based on environmental data from locations where it is known to occur.

Species distribution models allow us to:

- determine locations where a species may be able to live outside its existing geographical range; this can be useful for choosing reserve and restoration sites in species conservation
- look for rare species or species whose distribution is poorly understood with more accuracy; models help us know where we should look
- predict shifts in species distribution in response to climate change; this is useful for anticipating how climate change factors might affect a species in its current distribution.

In 1990 species distribution modelling was used to predict the possible further spread of the invasive cane toad in Australia. The CLIMEX model was used to examine the potential spread of the cane toad under conditions in 1990 and projected climate scenarios. This model is used to determine the relative climatic potential of areas for population growth and persistence of amphibians and reptiles. The model produced maps of potential habitat of the cane toad in Australia based on climate and occurrence data from Central and North America where the cane toad is native. The distribution of the cane toad in 1990 is shown in Figure 13.2.8.

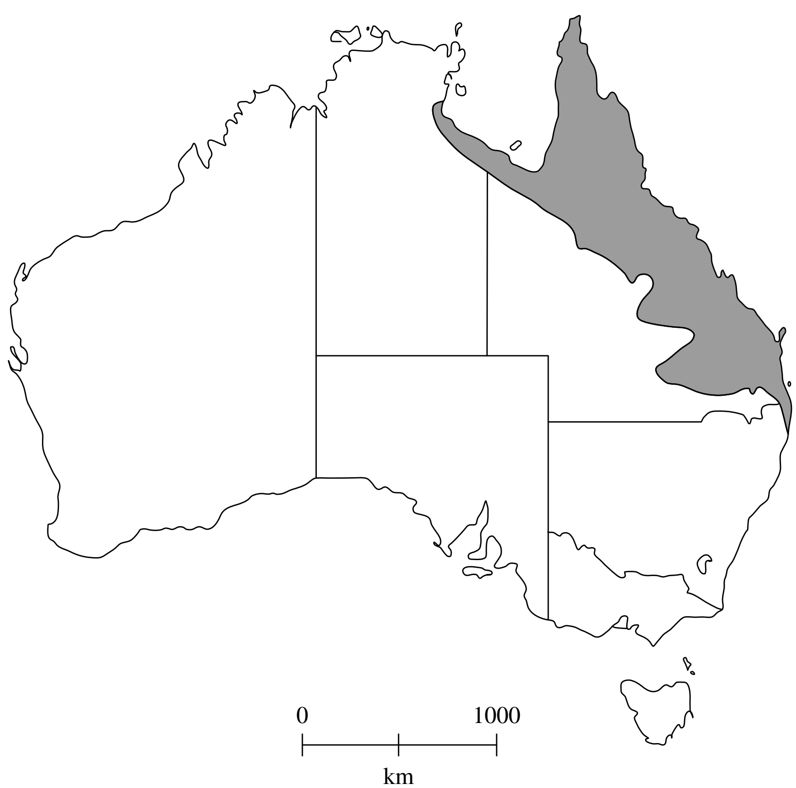


FIGURE 13.2.8 Distribution of cane toad (*Rhinella marina*) in Australia 1990

Outputs from the CLIMEX model predicted habitat suitability under the two scenarios shown in Figure 13.2.9: the persisting average climate of 1990 (a) and a climate-warming scenario (b). In this figure, the Ecoclimatic index shows the suitability of each location for cane toad colonisation.

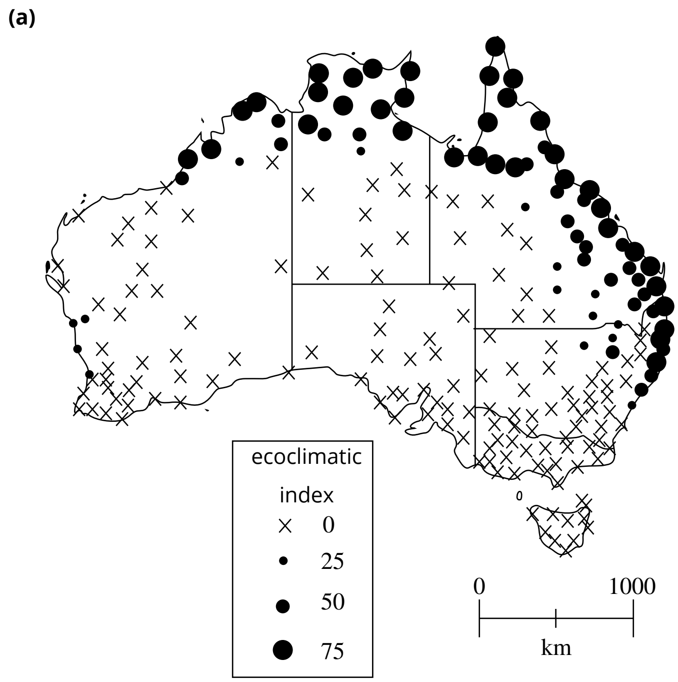


FIGURE 13.2.9 Outputs from CLIMEX model: average climate of 1990 (a) and a climate-warming scenario (b)

The distribution of the cane toad in 2004 is shown in Figure 13.2.10 (dark blue).

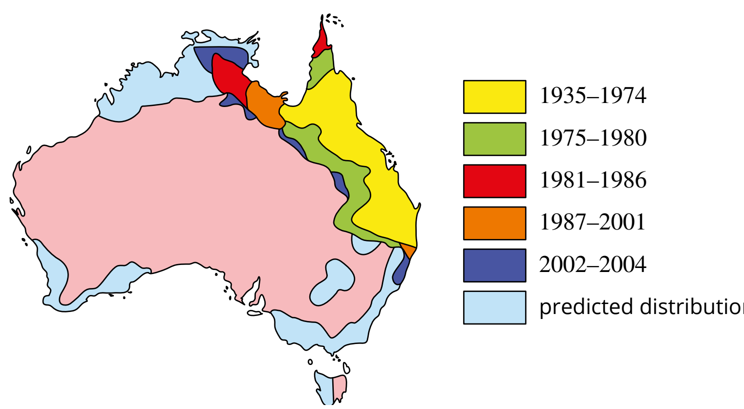


FIGURE 13.2.10 The cane toad's geographic distribution since its introduction to Australia in 1935 and its predicted distribution (light blue) as its range continues to expand

Species distribution modelling is not always perfect. So many variables account for the success of a species within a habitat and a model cannot make exact predictions. As models are used more and become more complex and advanced, accuracy is improved. Though they may never be entirely accurate they are very useful for anyone trying to anticipate habitat suitability for a species.

13.2 Review

SUMMARY

- Monitoring is the collection of data about a species or environment over time. It is used to assess the state of a system or population and record changes, allowing us to infer and understand reasons for those changes.
- Bioindicators are sensitive species that are used to measure environmental impacts. They can represent complex processes and are easier to measure than an array of environmental variables.
- Lichens are bioindicators used to detect levels of air pollution. Macroinvertebrates are used to determine water quality.
- Climate models use equations based on physical laws to represent climate processes. Existing climate data is used as the starting point for a climate model and time steps move the model forward.
- Global climate models are used to predict average climate conditions across Earth.
- Representative Concentration Pathways (RCPs) are four possible greenhouse gas trajectories for possible climate change scenarios.
- RCP 8.5 is a high emissions and warming scenario, RCP 6 and RCP 4.5 are intermediate scenarios and RCP 2.6 is a low emissions and warming scenario.
- Species distribution models use species occurrence and environmental data to predict potentially suitable habitats.
- Species distribution models can be useful for:
  - finding locations where a species may be able to live outside its existing geographical range
  - telling us where to look for a rare species or species whose distribution is poorly understood with more accuracy
  - predicting shifts in species distribution in response to climate change.

KEY QUESTIONS

1 Name four things that may be measured when monitoring water quality.

2 Give two examples of the types of organisms that are used as bioindicators. What do they indicate?

3 What happens to the global mean temperature under each RCP (Representative Concentration Pathways) scenario?

4 What aspects are included in a species distribution model?

5 What can species distribution models be used for? Give an example where a species distribution model has been used in Australia.

6 What is monitoring and why is it important for biodiversity and conservation?

7 Scientists cannot predict exactly what will happen to the global climate in the future but they can make projections about climate using global climate models. Briefly explain how climate modelling works and name some climate variables that are included in models.

8 **a** Which RCP represents a future where no action is taken to reduce greenhouse gas emissions?

b What are we likely to see happen if no action is taken to reduce greenhouse gas emissions?

9 **a** What is a bioindicator?

b What characteristics make an organism a good indicator species?

13.3 Managing and conserving biodiversity

People all over the world depend on different aspects of biodiversity every day. We are part of the biodiversity that currently exists on Earth and we rely on the rest of the planet's biodiversity for our own existence. We need biodiversity to grow food, we use timber for building and we use plants to make an extensive variety of medicines and other products.

Unfortunately, Earth is currently losing biodiversity faster than at any other time in human history. This will have a major impact on all remaining biodiversity including ourselves. While there is a struggle for survival between species in an individual ecosystem, all are dependent on the ecosystem functioning as a whole. Our survival depends on ensuring that species and ecosystems are not lost or damaged, so we have to improve the way we use and manage biodiversity as a resource.

THE VALUE OF BIODIVERSITY

Biodiversity holds different types of value for different reasons among different groups of people. A healthy biodiversity of organisms holds many benefits for humanity.

Direct practical value

Organisms have practical values for humans (Figure 13.3.1). The following are examples of biological resources provided by organisms:

- Food—more than 600 species of finfish and shellfish are caught and sold in Australia for human consumption.
- Medicines and drugs—about 25% of prescribed medicines contain natural plant compounds; many other prescribed medicines are synthetic versions of natural compounds.
- Industrial materials—including wood, fibres, dyes, resins, gums, rubber and oil.
- Ornamental plants—more than 2500 Australian native plant species are listed as useful in horticulture.
- Crop pollinators—39 of the 57 global crops benefit from natural pollinators such as birds and insects.
- Future resources—bioprospecting of new food and medicinal drugs.
- Engineering and design—biomimicry is a new branch of science that studies the structure and function of organisms and applies this knowledge to solve practical problems.
- Plants—for the restoration of waste land after mining.
- Diversity in genes, species and ecosystems—for example, diversity in genes and species can help to protect crops from devastating diseases, such as potato blight that caused a famine in Ireland in the 1840s.
- Breeding stocks and population reservoirs—maintaining genetically diverse wild or captive populations to ensure the continuity of species that may have practical values.

FIGURE 13.3.1 (a) Blue mussels (*Mytilus galloprovincialis*) are commonly grown in aquaculture farms. (b) The tea tree oil from the tea tree plant (*Melaleuca alternifolia*) has antiseptic properties. (c) The blue banded bee (*Amegilla cingulata*) is an Australian native bee that is very important for the production of at least 30% of crops in Australia, by assisting with pollination.

Ecological value

Plants, animals and microorganisms have ecological value by performing distinct functions within an ecosystem. The functions of ecosystems that also directly or indirectly benefit humans are known as **ecosystem services**. Plants are producers of food, and during photosynthesis they release the oxygen that we breathe. Rain, snow and the flow of rivers provide drinking water. Plants also provide shelter and nest sites for animals. Animals pollinate flowers, and many also disperse seeds (Figure 13.3.2). Predators keep prey numbers in check. All organisms depend on certain bacteria and cyanobacteria for nitrogen fixation in ecosystems. Fungi and bacteria decompose dead organic matter and recycle nutrients.

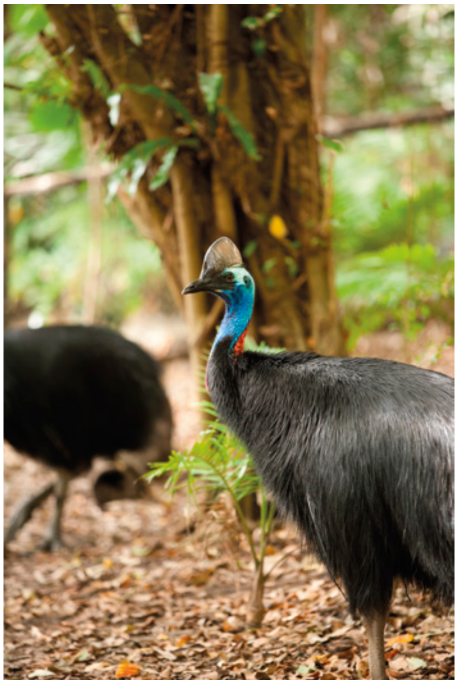


FIGURE 13.3.2 The southern cassowary (*Casuarius casuarius*) is an important disperser of rainforest seeds in north-eastern Queensland. Continuous clearing and fragmentation of rainforest and increased mortality from cars and dogs, have reduced cassowary numbers to perhaps as few as 2000, threatening the species with extinction.

Aesthetic value

Many people have an aesthetic appreciation for biodiversity and the beauty of nature. We enjoy the way it looks and makes us feel. This is why people pick colourful flowers, keep exotic fish or enjoy views of trees, mountains, lakes and wildlife (Figure 13.3.3). Biodiversity also inspires art and is often the subject of poems, songs and paintings.

FIGURE 13.3.3 Scenes like this one of pink flowers growing on the side of a mountain at sunset evoke feelings of happiness and contentment in humans.

Intrinsic value

Biodiversity has value regardless of its usefulness to humans. All living things are entitled to life; therefore, biodiversity has intrinsic value. The intrinsic value of all species means every living thing has value in its own right, and should be allowed to exist purely because it exists in the first place. This also means one species should not be valued more highly than another; for example, a mosquito and koala both have the same intrinsic value and right to life. These intrinsic values of biodiversity should be respected and humans have an ethical responsibility to prevent harm to other species and protect, conserve and restore ecosystems.

Social and cultural value

Biodiversity can hold value for many social and cultural reasons. In some cultures or religions different species may be considered holy or sacred and elements of biodiversity may be included in cultural identity and traditions. It may be important to some groups of people that a particular species be conserved because of a spiritual connection. In Indigenous Australian cultures totemic species have practical value as well as spiritual significance. Biodiversity also has recreational value. Bushlands are valuable to people who enjoy hiking, and maintaining healthy aquatic ecosystems is important to people who enjoy swimming and recreational fishing.

Option value

All of Earth's biodiversity has the potential to be useful and there may be many more uses of biodiversity that have not been discovered yet. Maintaining Earth's biodiversity is essential because it is a reservoir for bioprospecting new food sources and medicinal drugs. **Bioprospecting** is the exploration of biodiversity for new resources, such as chemical compounds and genetic material that has social or commercial value. If we allow species and ecosystems to become extinct we may lose the 'option' of making these discoveries.

Bioprospecting

FIGURE 13.3.4 The Muyan or silver wattle (*Acacia dealbata*)

Bioprospecting is the search for new plant and animal substances that have medicinal or other uses. This is not an entirely new thing to do. Indigenous Australians have been bioprospecting for a very long time. For example, the Wurundjeri people in Victoria have many uses for the Muyan or silver wattle tree (*Acacia dealbata*) (Figure 13.3.4).

The timber of the silver wattle is used for axe handles, and the bark is made into string for baskets and bags. Sap extracted from cuts in the wattle tree trunk can be mixed with ashes from a wood fire to make glue, or mixed with nectar from flowers to make a sweet drink. The wattle's seed pods can be cooked and eaten, or pounded to make flour. Currently there is research from all over the world into finding, developing and testing chemicals produced by a range of plants. The National Cancer Institute in the United States alone has tested 35 000 species of plants for anti-cancer properties. Testing is also being done for properties to fight other diseases such as cardiovascular disease, arthritis and AIDS. Bioprospecting relies on biodiversity conservation to ensure that all plant species can be investigated for potentially useful substances.

Well-managed bioprospecting can be advantageous because it can generate income for developing countries and can provide motivation for conservation and management. But if it is managed poorly it could result in environmental, social and economic problems. Problems can also occur if private organisations or individuals exploit knowledge of **bioresources** that they do not own without sharing the profits with Indigenous peoples. This is known as 'biopiracy'.

It is estimated that over 200 companies are screening plant and animal substances for drugs. About 20% of modern pharmaceutical drugs come from the Amazon rainforest (Figure 13.3.5). Interestingly, 90% of the drugs come from the Southern Hemisphere, but 90% of the people who use them live in the Northern Hemisphere. In 2010, which was the International Year of Biodiversity, the 10th Conference of Parties to the Convention on Biological Diversity adopted the Nagoya Protocol, which relates to access to bioresources and sharing of benefits. It specifically addresses the issue of bioprospecting and the rights of Indigenous people to access forest resources, intellectual property and adequate compensation. The Protocol has been signed by 92 countries, 53 of which have ratified it so far. It came into force in 2014.

FIGURE 13.3.5 The Amazon Basin contains the largest collection of living plant and animal species in the world, many of them not yet known. Pharmaceutical companies are scouting the rainforest for possible new drugs and tapping into the wisdom of traditional indigenous healers. A vast selection of plants, barks, roots and leaves from the rainforest are available in markets throughout the rainforest.

Most of the world's food supply depends on about 150 plant species, but only 12 species provide 75% of the world's food. More than half of the world's food energy comes from a limited number of varieties of three 'mega-crops': rice, wheat and maize. Sorghum, millet, potatoes, sweet potatoes, soybean and sugar provide another 25%. People living in poverty (almost half the world's population) depend on plants for as much as 90% of their needs (food, fuel, medicine, shelter, transport). Approximately 1.4 billion people, mostly resource-poor farmers, use and improve their own crop seeds to maintain and enhance the genetic variation of crops. It is vital to ensure continued genetic variation in these major crops to avoid vulnerability to diseases that could affect production worldwide. Plant and food research combines traditional breeding techniques with modern genetic techniques to develop better cultivars faster. Bioprospecting combined with genetic engineering could increase the diversity of food crops available.

DECISION-MAKING

The values placed on biodiversity determine which species or ecosystems receive the most attention in terms of conservation. Because the value of biodiversity can be subjective, different people and groups value biodiversity in different ways. There is no consensus on which species or ecosystems are most important to conserve.

One way to overcome this problem is to focus conservation efforts on the most threatened species and systems. The International Union for Conservation of Nature (IUCN) has created a Red List which can help to guide conservation activities. The IUCN Red List is a global inventory of threatened species and their conservation status. When a species is assessed it is put into a category depending on the level of threat that it faces. The categories are: Extinct, Extinct in the Wild, Critically Endangered, Endangered, Near Threatened, Lower Risk, and Least Concern. Some species may also fall under Data Deficient or Not Evaluated categories. Species that fall into the Critically Endangered category are of highest conservation priority because they are more likely to soon become Extinct.

Conservation triage

Unfortunately, human, funding and time resources are limited when it comes to conservation. Without more resources being allocated to conservation some projects are prioritised while others might have to wait. A systematic approach to deciding where to invest conservation resources is known as **conservation triage** and can be considered in the same way as triage in a hospital. In emergency medicine doctors constantly determine the priority of patients based on the severity of their condition and the resources available. In triage situations resources are insufficient for all patients to be treated immediately and resources are allocated to maximise the number of survivors. This means those who need critical attention are seen to first but only if the care they receive is likely to have a positive outcome. In terms of conservation the world is in a state of extinction emergency. It is possible that more species require conservation attention than we have time or money to conserve. A triage approach to conservation decision-making is controversial because it would mean abandoning the aim to conserve all species and ecosystems. Resources will be focused on conservation projects that would provide the best overall conservation results but some species could be left to go Extinct. For example, priority might be given to a species whose existence has a great effect on all others in an ecosystem (e.g. a top predator), and another species might not receive any assistance and eventually become Extinct.

SPECIES CONSERVATION

There is no global consensus as to what constitutes an important species. However, species that have a high value may be chosen for conservation because they fall into one of the following categories:

- species that are under threat of extinction
- species of ecological importance
- species that have economic value to humans
- species of cultural or social importance.

There are two main species-based conservation approaches: **in situ** and **ex situ**.

In situ conservation

In situ conservation involves keeping the species in its natural environment. This conservation approach involves:

- preserving the habitat through private purchase or government action
- eliminating invasive or pest species from the area
- managing protected areas to sustain native flora and fauna
- restoring degraded ecosystems.

BIOFILE S

Numbat breeding program

The numbat (*Myrmecobius fasciatus*) was once found in southern and central Australia (Figure 13.3.6). However, because of habitat destruction and the introduction of predators such as foxes and cats, the numbat is now found only in the Dryandra Woodland and Perup Nature Reserve in south-west Western Australia. The current population is about 1000.

As part of ex situ conservation, a breeding program has been established at Perth Zoo. In addition, numbats are also being reintroduced into managed predator-free sanctuaries such as Scotia Sanctuary in New South Wales.

FIGURE 13.3.6 The numbat (*Myrmecobius fasciatus*) population is rapidly declining. Populations of the numbat are stable only in managed predator-free habitats.

Ex situ conservation

Ex situ conservation involves protecting the animal or plant outside its natural habitat so threats to the species' survival can be managed or removed. This approach can involve:

- captive breeding with the possibility of reintroducing the organism to its natural habitat
- maintaining a captive population (e.g. in a zoo)
- conserving genetic variation by storing samples of seeds, pollen, tissues or cell cultures.

Many conservationists prefer the in situ approach because it means the species can interact with its environment, increasing its chance of survival. An ex situ approach is needed if the population size is critical or there is too much damage to the habitat.

BIOFILE S

The Endangered bilby

Before European settlement the bilby (*Macrotis lagotis*) occupied about 70% of mainland Australia. Today bilbies are found only in scattered, isolated populations in semi-arid to arid grasslands and acacia shrublands (Figure 13.3.7). Because of this the bilby is considered to be an Endangered species and is protected by law. Bilbies have been bred in captivity recently and released into the wild in the Currawinya National Park in south-eastern Queensland.

FIGURE 13.3.7 The bilby (*Macrotis lagotis*)

BIOFILE S

Protecting native species

In New South Wales, all native species of birds, reptiles, amphibians and mammals (except dingoes) are protected by the *National Parks and Wildlife Act 1974*. In addition, the *Threatened Species Conservation Act 1995* gives special recognition to species, populations and communities of plants and animals that are threatened by extinction.

The list of threatened species is extensive and includes 685 plants, 146 birds, 75 land mammals, 44 reptiles, 29 amphibians and 23 invertebrates.

Many aquatic plants, marine mammals, fish and aquatic invertebrates are also protected.

ECOSYSTEM AND HABITAT CONSERVATION

Some species have to be saved from the brink of extinction by growing them in special nurseries or breeding them in captivity, but saving species is best done by protecting and preserving habitats and ensuring that populations are stable or increasing. Rainforests, woodlands, heathlands, grasslands, wetlands and coral reefs are among the most endangered habitats on Earth.

One obvious reason for preserving areas of habitats is that it ensures the protection of a diverse range of organisms. There are many species in a pond, or in the litter of a eucalypt forest, that we rarely see. Scientists believe there are also a huge number of species of insects, spiders, crustaceans, plants, protists, fungi and bacteria that are yet to be discovered. They are all part of the food web and they are all important in maintaining the balance of the ecosystem.

Some types of habitats are especially important to conserve because they support a large range of biodiversity. Areas that contain large numbers of species, especially endemic species (species that are only found in one area of the world) are often referred to as 'biodiversity hotspots' (Figure 13.1.1). Concentrating conservation efforts in these areas can help to maintain global biodiversity.

Conservation of habitat also protects the interrelationships between organisms. For example, the broadleaf ballart (*Exocarpos latifolius*) found in northern Australia is the food plant for the larval stages of a butterfly known as the fiery jewel (*Hypochrysops ignitus*). The broadleaf ballart is also a parasitic tree so it relies on a host tree species for its survival (Figure 13.3.8).

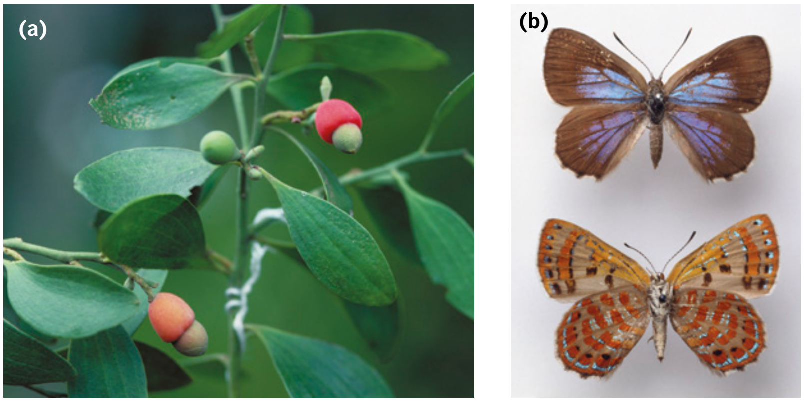


FIGURE 13.3.8 The broadleaf ballart (*Exocarpos latifolius*) (a) is the food plant for the larval stages of the fiery jewel (*Hypochrysops ignitus*) (b).

Establishing protected areas

Habitat loss is considered to be the primary cause of biodiversity loss around the world. To counter this, governments establish **protected areas**. Effective management of protected areas is essential to deal with human settlement, illegal harvesting or poaching, unsustainable tourism and impacts of alien species.

BIOFILE S

Restoring regent honeyeater habitat

The regent honeyeater (*Anthochaera phrygia*) (Figure 13.3.9) was once found throughout temperate woodlands and forests in south-eastern Australia. Today there are only a few fragmented populations in New South Wales and Victoria. The loss of woodland is the major cause of the decline, and continues to be a threat to the species. As part of conservation efforts, natural habitats of the regent honeyeater are being restored. For example, the regent honeyeater's native woodland habitat in the agricultural district of the Lurg Hills near Benalla in Victoria was restored by the community through revegetation.

FIGURE 13.3.9 Efforts are being made to protect the habitat of the regent honeyeater (*Anthochaera phrygia*) to ensure that it continues to survive in the wild.

Designing reserves

Throughout the world, governments put aside land for the preservation of animals, plants and ecosystems. Some **reserves** in the world are very large, covering thousands of square kilometres, such as the swamps of the Florida Everglades. But important reserves can also be quite small. For example, narrow reserves along roadsides and railway lines are important for many small animals and plants. Even home gardens can be important sources of food and nectar for birds. In Australia, Kakadu National Park, the Wet Tropics of Queensland, Lord Howe Island and the Great Barrier Reef are all listed as World Heritage Sites, which recognises their global importance (Figure 13.3.10).

FIGURE 13.3.10 World Heritage Site the Great Barrier Reef is the world's largest coral reef. It covers 348 000 km^2: larger than the United Kingdom, Netherlands and Switzerland combined.

Reserves that are small or fragmented may be unsuitable for animals that need large territories to search for food, build nests or find mates (Figure 13.3.11). Populations can become fragmented into small groups with a low genetic variation. Small reserves are also more vulnerable to destruction. For example, a small group of trees can be damaged more severely by wind storms than a more extensive forest, where the trees buffer one another. Events such as fires and floods could also destroy a small reserve or make it uninhabitable for many species, and the animals might not be able to reach other suitable habitat.

FIGURE 13.3.11 Chobe National Park is a protected area of 21 000 km^2 in Botswana and is home to about 50 000 elephants. Damage caused by the elephants is extensive in some areas and culls have been considered but are too controversial.

If animals cannot find all the resources they need in a small fragment of habitat, especially food, they must try to reach other suitable habitat. Some small animals such as butterflies and birds are especially vulnerable to habitat fragmentation because they will not fly across clearings, even the width of a road.

Organisms in small reserves are more likely to be exposed to edge effects because of the relatively large length of the edges compared to the area of the reserve. Edge effects include an increase in sunlight and temperature, exposure to wind, lower humidity and greater chance of invasion by pest plants and animals. The abiotic environment is quite different from the cool, dark, moist forest floor within the rainforest. Many organisms are not adapted to survive in the drier edge microhabitat (Figure 13.3.12).

FIGURE 13.3.12 The environmental conditions at the edge of a reserve can be very different from those in the middle.

RESTORATION OF DAMAGED ECOSYSTEMS

To accommodate the growing human population huge areas of Earth's natural environment have been changed or destroyed. Many ecosystems have been disturbed to the point where the functions and structure of ecosystems have been lost. This has occurred on land from logging forest, intensive grazing and building cities and roads, and in aquatic environments by creating dams, using boats and polluting waterways.

Ecosystem restoration aims to return an ecosystem to the state it was in before a disturbance occurred. Restoration projects may focus on reintroducing the species composition of an area, removing invasive or pest species and relieving a disturbance pressure.

BIOLOGY IN ACTION AHC CC

Traditional knowledge for improving biodiversity

Fire is a natural part of the Australian environment. Many species and communities require fire to reproduce and stay healthy (Figure 13.3.13). For thousands of years Aboriginal communities have used fire to manage and care for the land. Traditional fire regimes require an enormous amount of knowledge about the species and communities within an ecosystem to know when, where and how to burn. Traditional fire management relies on cool, quick, low-intensity fires. This kind of burning technique does not damage upper layers of the forest and protects the seed bed and animals within. The canopy remains intact, acting as a refuge for animals during the fire while shade cover remains for protection of ground-dwelling organisms after the burn. Low-intensity fires also promote germination of new plants. A succession of these cool burns over various areas of space and time create a mosaic effect of burnt, regenerating and established areas that each house a different set of organisms. Traditional fire techniques also decrease the chances of a large high-intensity fire coming through and wiping out vast numbers of plants and animals.

The arrival of European settlers resulted in a major change in the way fire was used to manage land. The displacement of Aboriginal people changed the prevailing fire regime. European agriculture required large areas of land to be cleared using hot, intense burns while naturally occurring bushfires were prevented or suppressed to protect areas of settlement. Since Europeans colonised Australia over 200 years ago, a substantial amount of biodiversity has been lost. Traditional knowledge and fire regimes are now being incorporated into conservation and land management techniques all over the country to help improve biodiversity.

FIGURE 13.3.13 (a) Traditional fire regimes are an important part of Australian ecosystems. (b) Regular low-intensity fires are required for the regeneration of many native species.

Mining site restoration

Mining operations cause considerable environmental impacts of erosion, biodiversity loss and contamination of soil and water. The construction of a mining site and its infrastructure changes the land use of an area resulting in major habitat modification and destruction. Unfortunately, areas with geological formations that are prospectively useful for mining are also often areas of high conservation value supporting rare ecosystems or endemic species (Figure 13.3.14).

Mining is an important part of the Australian economy, accounting for over half of the value of national exports. Australia has significant reserves of minerals and resources including iron ore, nickel, aluminium, copper, gold, silver, uranium, opals, zinc, coal and natural gas. Land used for mining makes up less than 1% of Australia's total land area but still has damaging effects on the environment. Australian law requires mining companies to minimise the environmental impacts of their operations. One tool that is used is the ecological restoration of mining sites

once a mine is closed. Mining is a temporary activity relying on finite resources where operations at a site eventually cease. The land at a mining site is generally severely degraded in terms of ecosystem function. In the industry restoration of mining sites is referred to as 'rehabilitation', with the aim of returning land and water to productive use and recreating sustainable ecosystems that integrate with the surrounding area.

Approaches to mining reclamation depend largely on the physical and geochemical properties of the area, the type of mining operations that occurred and the ecosystem that is to be restored. Mining sites differ greatly in these aspects so each site must be considered case by case. Generally, rehabilitation of all mining sites requires the following:

- Clean up of contaminants—contaminants and waste products from the mining operation are contained or removed to prevent the release of toxic chemicals or acid drainage into the environment.
- Land form reconstruction—excavation during the mining process alters the initial topography of the land. Landforms must be reconstructed and stabilised to allow for appropriate drainage and to minimise erosion. Deep holes and steep slopes from waste piles are reshaped.
- Soil restoration—once land forms are stabilised, soils must be restored to sustain plant growth. During the mining operation, important nutrient-rich topsoil is generally set aside and stored. This soil is then respread over the rehabilitation site and may be supplemented with appropriate fertiliser. Contours are created to assist with drainage and mulch or tree debris is spread to mimic natural conditions and prevent erosion.
- Revegetation—restoration of a stable ecosystem relies on successional establishment of the plant community. Some seed reserves may still be present in the topsoil and can re-establish, sowing of seeds or planting individual plants and seedlings may be required, or recolonisation from species in surrounding areas may occur.
- Fauna recolonisation—restoration of the plant community can allow animals to recolonise without human intervention, though full habitat restoration is complex and can take a long time. If components of the habitat are missing, additional resources and support for animal species may be required such as constructing nesting boxes or feeding stations and controlling pest species.

Rehabilitated mining sites require constant monitoring through the restoration process and once the ecosystem has been re-established.

FIGURE 13.3.14 Ranger Uranium Mine in Kakadu National Park, Northern Territory Australia. Kakadu National Park is a protected area important for conservation, but it also contains large uranium deposits important for the mining industry.

Restoring degraded agricultural land

Conversion of natural ecosystems and environments to agricultural land has drastic impacts on biodiversity and productivity. In Australia over 60% of the continent's land area is used for agriculture but only a very small part of that land is naturally suitable for growing crops. Agricultural practices such as irrigation and use of fertilisers have allowed crops to be grown in areas that are not usually arable. Agricultural land use also relies on clearing native vegetation to create pastures for grazing and cropping. Unfortunately, these practices are not always sustainable and result in degraded land that cannot support further agriculture or native species and functional ecosystems.

The main causes of land degradation in agricultural areas are:

- Overgrazing—high grazing pressure from having too much stock in an area or high numbers of grazing pest species can damage vegetation cover. Intensive grazing over long periods of time does not allow for vegetation to recover, which can cause soil erosion and desertification in arid areas.
- Removal of vegetation—clearing native plant species leaves soil susceptible to erosion from wind and water. Soil is protected by vegetation cover and when it is removed wind can blow soil away or rainfall can wash soil down slopes along with important nutrients. Removal of deep-rooted vegetation can also cause changes to water moving through the soil profile. More water is free to move, depositing dissolved salts and increasing soil salinity and making the soil unfavourable for many plant species to grow.
- Over-irrigation—irrigation can cause land degradation if more water is applied than plants can use. This can occur in areas with poor drainage or leaky soils. When water in the soil is not able to be dispersed, groundwater rises to the surface. This causes soils to become waterlogged and increases soil salinity as dissolved salts rise with the water.
- Unbalanced fertiliser use—using fertilisers is important for growing crops but if fertilisers are applied inappropriately plants do not use up the nutrients and leaching occurs. Use of nitrate-containing fertilisers can cause soil acidification where nitrates leach through the soil and pH decreases. Acidic soils become infertile as most plants can only grow between pH 5 and 8.

Restoration of degraded agricultural land can only occur when the pressures of agriculture are decreased or removed and steps are taken to improve soil quality so vegetation and biodiversity can re-establish.

FIGURE 13.3.15 Ord River Irrigation area covering about 22 000 ha, East Kimberley region, Western Australia

Peniup restoration project

In 2007 a restoration project was set up on a property called Peniup in Western Australia (Figure 13.3.15). Peniup had previously been farmed and significant areas of the property were cleared for running sheep and crops. **Remnant** woodland vegetation covered 27% of the property area. The aim of the project was to protect existing bushland on the property and restore habitats and native biodiversity in the areas previously used for agriculture. The project covers a large area that would naturally include a diverse landscape and species association.

Through analysis of spatial data, soil testing and biophysical information a detailed map was created describing the different soil and landscape types across 950 ha of the property. This map informed ecologists about the different plant communities that would typically be found across different areas of the cleared landscape. Nine vegetation associations were identified and seeds and seedlings of a mix of species specific to soil types and landscape positions were planted in appropriate areas. To maintain local genetics, 120 species were collected from the remnant vegetation in the surrounding area. Weed control and management were used to ensure pest species did not colonise the area.

Monitoring of 42 permanent sampling sites over the landscape of the project has shown patchy establishment of plant density and growth. This is expected in a diverse landscape and important for providing a variety of habitat types. It was also found that many seedlings did not survive the first hot, dry summer. In some areas new seedlings emerged a few years later and replaced those that had died.

Reducing pollution to protect species

Pollution created by humans can poison all forms of life on land and in water, and it is contributing to climate change. Transport, industry, construction, mining, power generation, volcanoes and bushfires all contribute polluting substances to the environment. These substances can directly cause death or disease in organisms, or alter the chemistry of the environment so that it is unfit for some organisms (Figure 13.3.16).

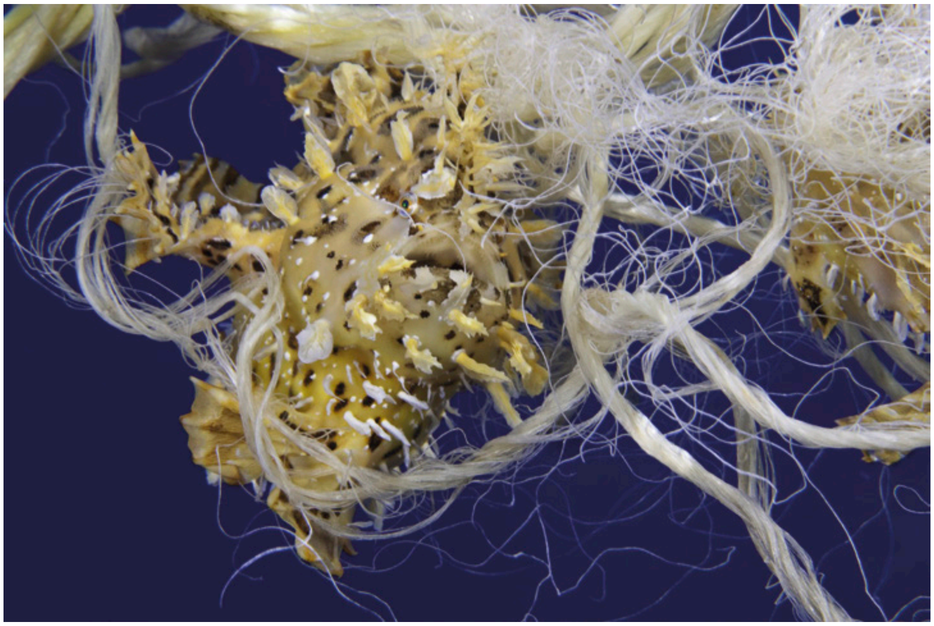


FIGURE 13.3.16 A sargassum fish (*Histrio histrio*) tangled in a discarded plastic rope

We can protect vulnerable species by reducing pollution. While industry has a major role to play in this, you can try to minimise your impact by:

- walking or cycling instead of travelling by car
- driving a car that uses less fuel
- turning off electrical appliances when they are not being used
- choosing energy-efficient appliances
- using environmentally friendly cleaning products, reducing the amount of phosphates and nitrates going into waterways
- reducing the amount of rubbish you generate by recycling and composting, and repairing rather than replacing goods
- limiting your use of chemical fertilisers, pesticides and herbicides and using environmentally friendly alternatives.

Combating climate change

Climate change is threatening many species that cannot evolve fast enough to cope with the increase in temperature. Extreme weather events may also pose a threat. Climate change will affect the abundance and distribution of organisms and will influence the crops we grow. If we can halt the increase in carbon dioxide levels we may be able to prevent the devastating effects of climate change on species, habitats and ecosystems. International agreements such as the Kyoto Protocol aim to reduce the emissions of carbon dioxide worldwide, but not all countries are signatories to such agreements.

BIOFILE S

The mountain pygmy-possum and climate change

The tiny mountain pygmy-possum (*Burramys parvus*) (Figure 13.3.17) could become a victim of climate change. It needs a snow depth over winter of at least 1 m to provide enough insulation to keep it warm during hibernation. Snow compaction, the removal of boulders and vegetation cover, and the development of ski fields, villages, car parks and roads have fragmented the pygmy-possum's habitat. Warmer temperatures could reduce the winter snow cover, exposing the animals to colder temperatures and making it even harder for them to survive the winter. A recovery plan for this species includes:

- establishing wildlife corridors to link populations that are separated
- revegetating damaged habitats
- minimising the environmental impact from skiers
- monitoring populations regularly
- eradicating introduced predators, including foxes and cats.

FIGURE 13.3.17 The mountain pygmy-possum (*Burramys parvus*)

Regulation to counter overexploitation

Biodiversity is exploited mainly for food (meat, vegetables, fruits) and construction materials (e.g. timber), but also for industrial products, the pet trade, fashion and medicines. Most species can tolerate some exploitation without it affecting the survival of its populations. However, overexploitation can push species towards extinction, upset the normal relationships between species in an ecosystem, and harm other species. For example, hunting a particular bird for food could reduce its numbers to an unsustainable level, reduce the food available to predators or cause predators to switch to another prey, and affect the survival of plants that depend on the bird for pollination or seed dispersal.

Overexploitation usually occurs because there is an economic benefit for those who are exploiting the species. The economic benefit creates an incentive for those people to continue exploiting the species or ecosystem despite the long-term costs of loss of biodiversity and ecosystem services.

WS 4.7

Overexploitation can often be managed by making strict laws and enforcing them, but this is often difficult to do in practice. For example, poachers in Southern Africa will risk their lives to kill a rhinoceros for its valuable horn. The horn is sold as an ornament or more commonly ground up for use in traditional Chinese medicines, even though there is no scientific evidence that shows the therapeutic benefit of rhino horn keratin. It is illegal to trade rhinoceros horns; however, they fetch a very high price on the black market. Sometimes rangers at private game reserves remove rhinoceros horns from live rhinoceroses as a deterrent to poaching. Even so, rhinoceroses are still killed by poachers for the remaining horn stub or as an act of vengeance.

13.3 Review

SUMMARY

- Species should be conserved because they have direct practical value, intrinsic value, aesthetic value, social/cultural value, ecological value and option value.
- Saving species is best done by saving habitats or entire ecosystems, because species must interact with other species and do not live in isolation.
- Strategies for conserving biodiversity include:
  - in situ conservation, where the species is maintained in its natural environment
  - ex situ conservation, where the species is grown or bred in captivity
  - establishing protected areas
  - controlling existing pest species
  - preventing new pest species from entering the country
  - reducing pollution to protect species
  - combating climate change
  - preventing overexploitation by legal and practical means.
- Ecosystems can be used by humans without destruction of habitat and loss of species.
- The use of ecosystems should be sustainable, meaning that resources should be used no faster than they can be replaced.

KEY QUESTIONS

1 Outline why maintaining biodiversity is important.

2 List the types of values possessed by a species that warrant its conservation.

3 Describe the two main conservation strategies outlined in this chapter (in situ and ex situ).

4 Define bioprospecting.

5 Our native plant and animal species are a priceless resource.

  a Explain the argument that species should be saved because they have ecological value.

  b Name an Australian species that is endangered and explain why it should be saved using the three reasons listed in the text as a guide.

  c For the Australian species that you have named in part b, outline the strategies currently used to conserve the species.

Chapter review

KEY TERMS

anthropogenic pressure
biodiversity
biodiversity hotspot
bioindicator
bioprospecting
bioresource
competitive exclusion principle
conservation triage
ecological niche
ecosystem restoration
ecosystem service
endemic
eutrophication
ex situ
extinction
gene flow
generalist
genetic variation
habitat
habitat fragmentation
in situ
inbreeding
invasive species
macroinvertebrate
model
monitoring
overexploitation
pollution
protected area
remnant
Representative Concentration Pathway
reserve
resource
specialist
species distribution model
symbiotic
trend

REVIEW QUESTIONS

1 How can human activity impact on an ecosystem? Consider both the abiotic and biotic factors in an ecosystem.

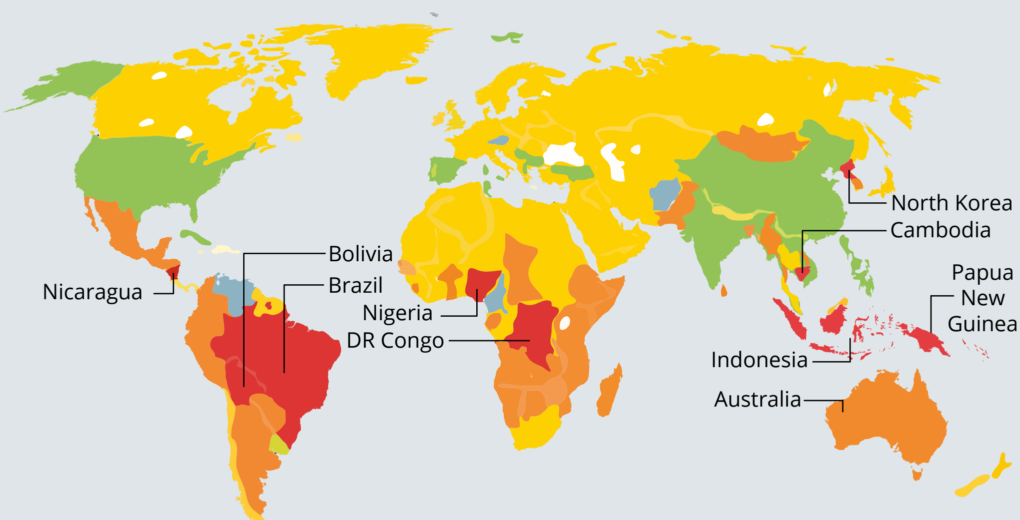
2 Select an ecosystem. Describe the human activities that occur in or around this ecosystem and the direct and indirect impacts they have had.

3 Do human activities have to occur in or near to an ecosystem to impact it? Provide an example to support your answer.

4 **a** How have human activities changed the habitats of Australian species over the last 200 years?
b Have these changes led to an increase or decrease in biodiversity?

5 Map 1 below shows the deforestation index for various parts of the world. This index is a measure of the risk of deforestation. Map 2 on the next page shows the biodiversity hotspots (highlighted in green) around the world. These are areas where biodiversity is unusually high.

Map 1

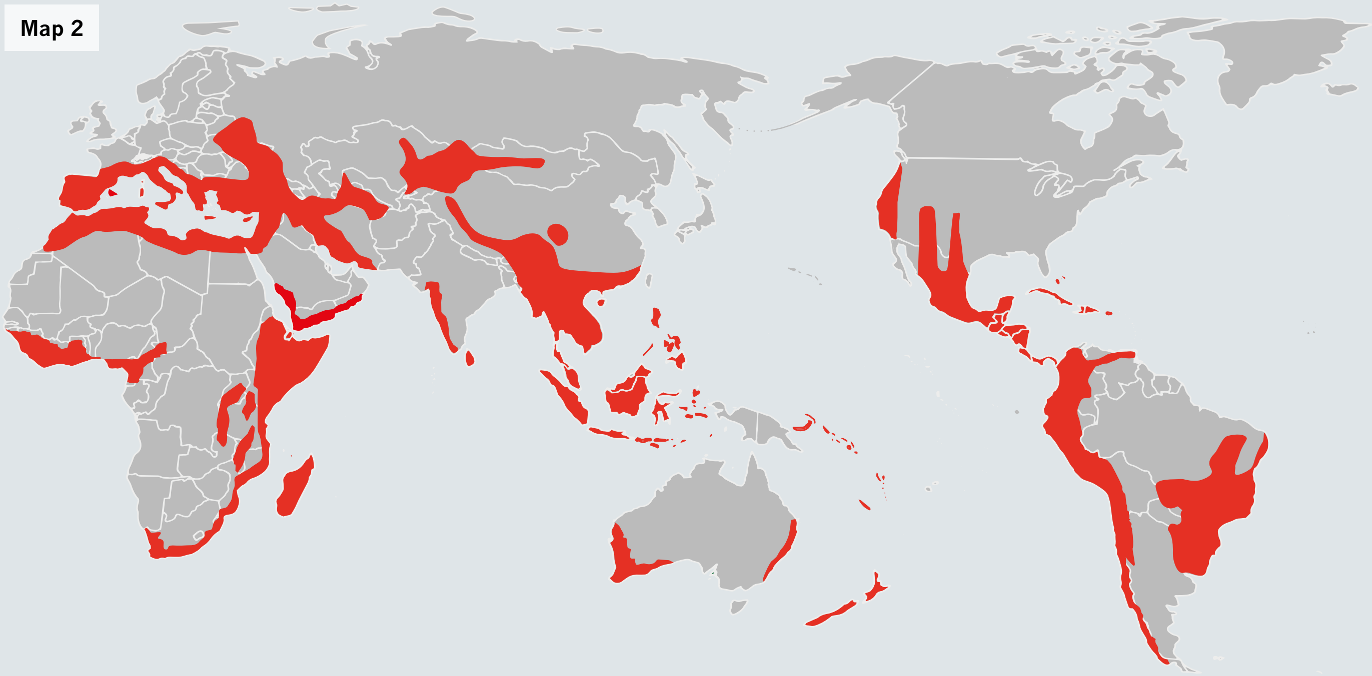


Legend	
extreme risk	red
high risk	orange
medium risk	yellow
low risk	green
no data	blue-grey

Rank	Country	Rating
1	Nigeria	extreme
2	Indonesia	extreme
3	North Korea	extreme
4	Bolivia	extreme
5	P.N.G.	extreme

Rank	Country	Rating
6	DR Congo	extreme
7	Nicaragua	extreme
8	Brazil	extreme
9	Cambodia	extreme
10	Australia	high

Map 2



a Define the term ‘biodiversity’.
b In which areas is biodiversity at the greatest risk from deforestation?
c Explain why it is essential to protect biodiversity hotspots.
d Most of the areas at extreme risk of deforestation are along the equator, where most of the tropical rainforests are found. Discuss the economic reasons for the conservation of tropical rainforest biodiversity as a form of in situ conservation.
e Invasive species have had a big impact on Australian biodiversity. Define the term ‘invasive species’.

6 The image below is an aerial view of forested (left) and deforested (right) areas. Outline five differences in biodiversity and/or ecosystem processes between the two areas.

7 How does habitat fragmentation contribute to biodiversity loss and species extinction?

8 What are invasive species and what are some common characteristics of invasive species?

9 a Name an invasive species in Australia.
b Name an Australian species that has become invasive in another country.

10 Outline some methods for controlling invasive species.

11 Explain the ways in which an invasive species can have significant impact on the survival of a native species.

12 Which of the following best describes a global climate model?
A A two-dimensional grid only on the surface of the Earth
B A three-dimensional grid where equations describe climate processes
C A vertical column at one specific location on Earth
D Equations explaining precisely what is happening at every single point around the globe

13 Why should we conserve biodiversity? Discuss at least four values of biodiversity to support your argument.

14 Do some ecosystems have higher biodiversity value than others? If so, provide an example of an ecosystem with low biodiversity value and an ecosystem with high biodiversity value.

15 The world's human population is more than 7 billion. By 2100 the human population could be 12 billion. In order to sustain this number of people, more land will have to be used to grow crops that are consumed directly by humans or fed to stock that are used to produce food for humans.
   a What are the implications of human population growth and activities for the biodiversity of the planet?
   b Outline two reasons why biodiversity is important.

16 Discuss the reasons for ex situ conservation of Endangered species.

17 Discuss the reasons for in situ conservation of Endangered species.

18 What is the purpose of establishing protected areas?

19 a List three examples of protected areas in New South Wales. You may already know of some examples or you can use the internet for research.
   b What makes these areas a priority for protection?

20 List three of the main causes of land degradation in agricultural areas.

21 After completing the Biology Inquiry on page 572, reflect on the inquiry question: How can human activity impact an ecosystem? Using at least five key terms from this chapter, describe how human activity can have both positive and negative impacts on an ecosystem.

MODULE 4 • REVIEW

REVIEW QUESTIONS

Ecosystem dynamics

WS 4.8 WS 4.9 MR 4

Multiple choice

1 Many lichens grow on the bark of trees. The relationship between the lichens and the trees is:

A parasite–host
B symbiosis
C mutualism
D commensalism

2 Herbivorous insects such as termites make use of protozoans in their gut to digest wood. Which of the following best describes this feeding relationship?

A herbivore food chain: wood → termite → protozoan
B parasite food chain: wood → termite → protozoan
C detritivore food web: wood → termite + symbiont
D decomposer food chain: wood → protozoan → termite

3 Which one of the following best defines the term 'food web'?

A the variety of food that a top carnivore eats
B a combination of different heterotrophs
C a long food chain with at least four trophic levels
D a diagram that shows all the feeding interactions in an ecosystem

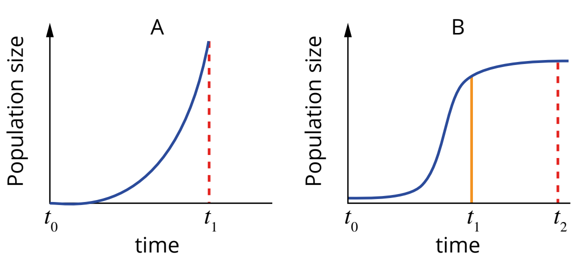
4 Select the list that contains only decomposers and detritivores.

A algae, bacteria, termites, echidnas
B vultures, ticks, earthworms, fungi
C millipedes, earthworms, bacteria, fungi
D snails, maggots, dung beetles, crows

5 Which one of the following is a density-dependent factor?

A rainfall
B fire
C temperature
D food supply

6 The following two graphs show the population growth of species A and species B. Which of the following statements is correct?



A Species A shows an exponential population growth between times $t = 0$ and $t = 1$, but species B does not.
B Species B has reached the carrying capacity of the ecosystem by time $t = 2$.
C No deaths occurred in species A or B between times $t = 0$ and $t = 2$.
D The graph for species B is typical of an insect population such as a locust plague.

7 Which of the following is an example of an anthropogenic disturbance?

A earthquake
B pollution
C volcanic activity
D flooding

8 How do stable ecosystems self-regulate?

A negative feedback loops
B positive feedback loops
C exponential growth
D logistic growth

9 For which of the following could you use carbon dating?

A igneous rocks from a volcanic eruption
B samples of shells and bones
C ice cores
D stone tool artefacts

10 Which of the following statements about radioactive decay is true?

A All isotopes decay at the same rate.
B The rate of radioactive decay increases with time.
C Radioactive decay occurs at a regular measurable rate for each isotope.
D The rate of decay for most isotopes is unknown.

11 Gas analysis of ice cores in Antarctica has shown which trend over the last 100 years?

A Atmospheric concentrations of greenhouse gases have increased.
B There has been no change in atmospheric concentrations of greenhouse gases.
C Atmospheric concentrations of greenhouse gases have decreased.
D Global temperatures have decreased.

12 What type of environment are sclerophyll plants adapted to?

A tropical climates with nutrient-rich soils
B wetlands and estuaries
C harsh, dry climates and nutrient-deficient soils
D mangrove swamps

13 Which of the following was a supercontinent that once included Australia?
A Laurasia
B Gondwana
C Antarctica
D Siberia

14 Which of the following best describes biodiversity hot spots?
A Regions with high biodiversity and a lot of habitat destruction.
B Regions with low biodiversity and no threat to habitat.
C Regions with high biodiversity and no threat to habitat.
D Regions with low biodiversity and a lot of habitat destruction.

15 Why is it that when habitat is fragmented, smaller population sizes lead to extinction?
A Small populations are unable to breed.
B Individuals will always migrate out of the area.
C Gene flow is restricted and inbreeding occurs.
D There are too many individuals in one habitat.

16 What are climate models used for?
A describing the exact climate in a specific location at a specific time
B interpreting existing climate and weather data
C predicting average climate trends over time under a range of scenarios
D explaining global warming

17 Lichens are used as bioindicators to detect levels of which one of the following?
A water quality
B air pollution
C soil salinity
D fire disturbance

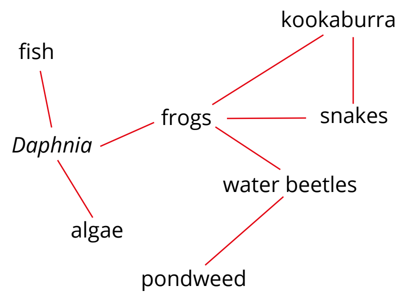
18 What is bioprospecting?
A captive breeding programs for plant or animal species used in conservation
B traditional fire regimes implemented by Indigenous Australian communities
C restoration of damaged waterways
D the exploration of biodiversity for useful substances such as chemical compounds for medicine

19 How can an individual minimise their impact on biodiversity and help to reduce pollution?
A always purchase foodstuffs packaged in plastic
B reduce the amount of rubbish generated by recycling and composting, and repairing, rather than replacing, goods
C use products that increase the amount of phosphates and nitrate in waterways
D drive a car whenever possible

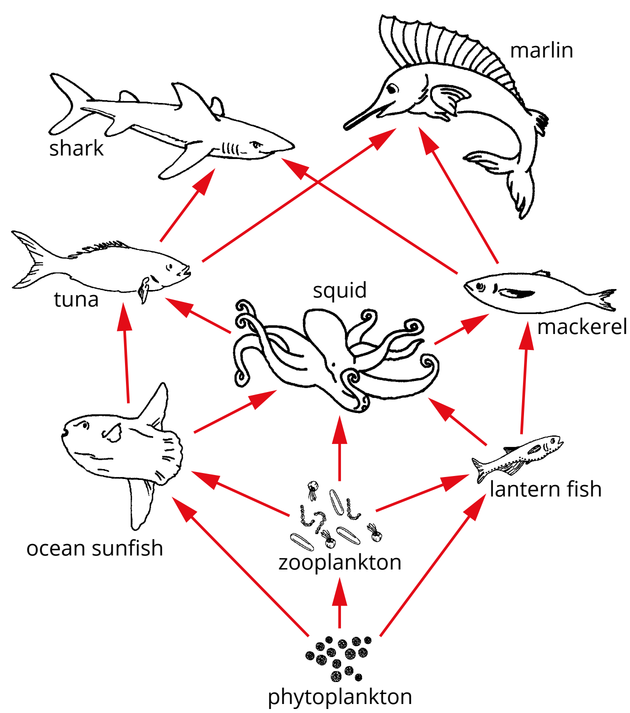
20 How can habitat fragmentation lead to loss of biodiversity or extinction of species?
A Small isolated populations have restricted gene flow, reducing genetic variation and leading to inbreeding.
B Different abiotic environments are found at the edges and middle of a habitat.
C Fragmented habitat might not include all necessary resources for all species.
D All of the above

Short answer

21 **a** What do the arrows in a food web represent?
b Draw the arrowheads on the diagram to complete the food web.



22 Examine the following food web and then answer the questions that follow.

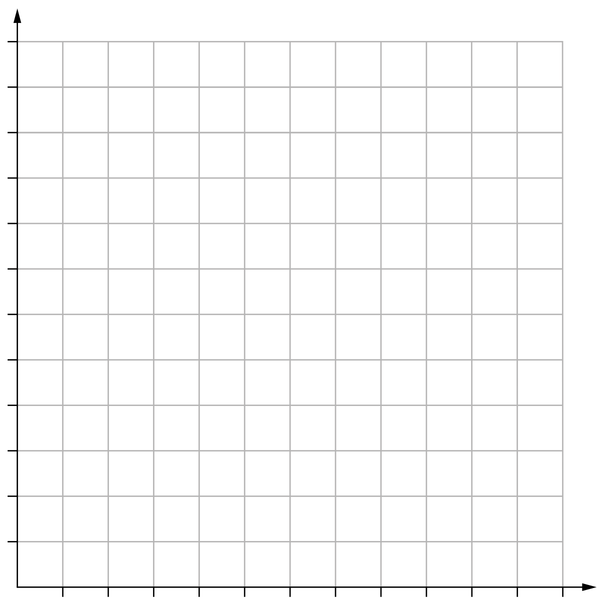


a What is the highest number trophic level in this food web?
b What roles do the phytoplankton, zooplankton and tuna play in this food web and why?

23 Complete the table by listing the six different types of consumers and what they eat, and include two examples of each type of consumer. The first has been done for you.

Type of consumer	What it eats	Examples
herbivore	plant matter such as leaves, seeds and fruits	sheep, koala

24 **a** On the graph below plot the relationship between disturbance and biodiversity according to the intermediate disturbance hypothesis. Label both axes.



b Why is diversity found to be low when the level of disturbance is low?

c Why is diversity found to be low when the level of disturbance is high?

25 What information can Indigenous Australians' rock art provide about past ecosystems? Give an example.

26 Briefly describe what happened to the climate and the vegetation in Australia after its separation from the Gondwanan supercontinent over the period of 132–96 million years ago.

27 Give three reasons why habitat destruction may occur.

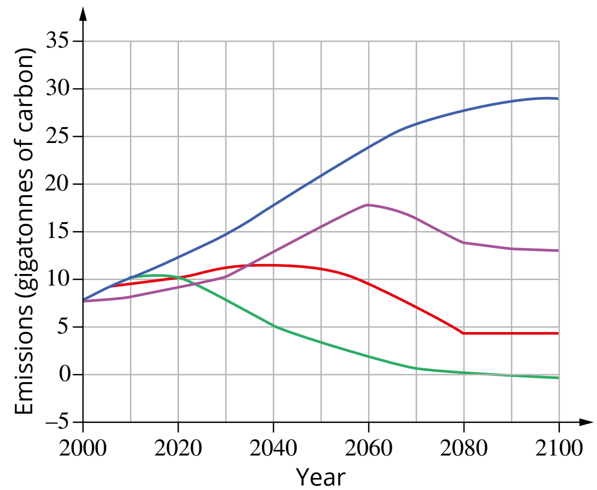
28 Give one example of a species threatened by climate change and one example of a species extinction caused by climate change. How has climate change affected these species?

29 Climate modelling uses four Representative Concentration Pathways (RCPs) as a range of possible scenarios for the future of greenhouse gas emissions and global warming on Earth.

a On the graph below, each coloured line represents a different RCP. Label each line.

b Briefly describe what happens in term of emissions and warming under each scenario.

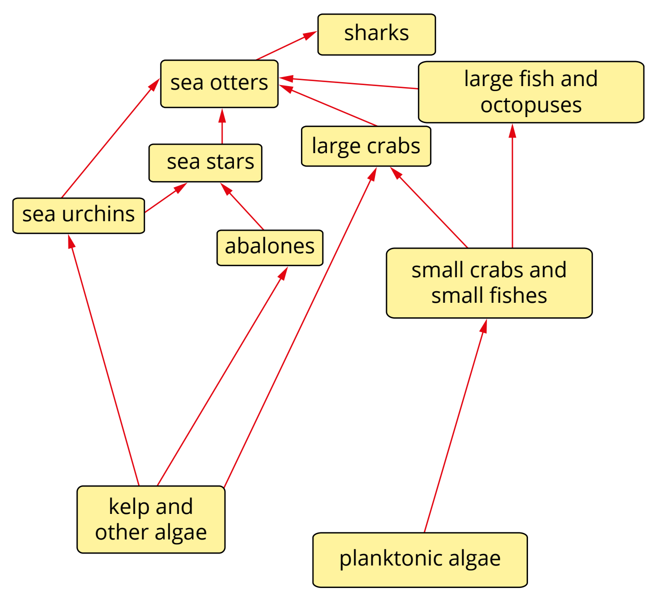
RCP carbon dioxide emissions trajectory between 2000 and 2100



30 List three strategies for conserving biodiversity.

Extended response

31 The following diagram shows a kelp forest food web.



a Identify the primary producers in this food web.

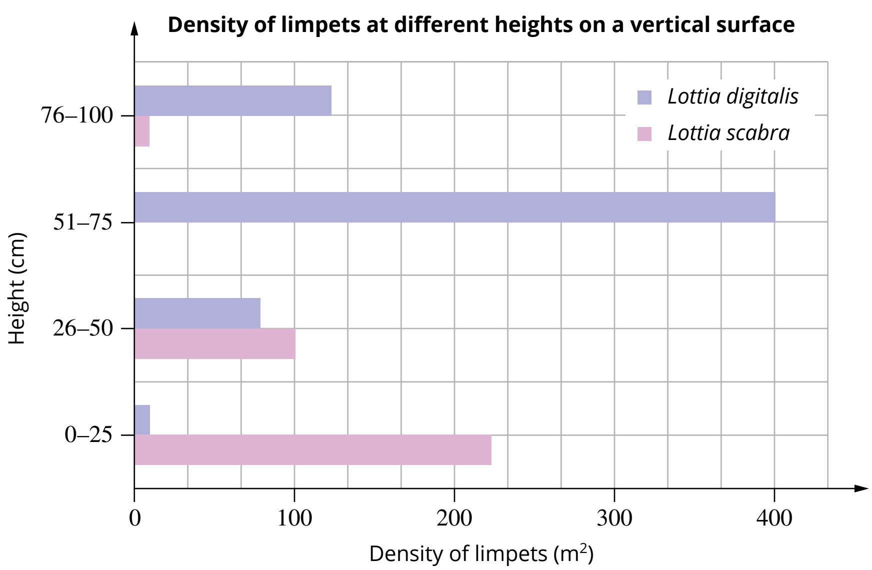
b Write down one food chain that involves four trophic levels.

c The sea otter is a keystone species in the kelp forest. Define the term 'keystone species'.

d Explain what would happen if sea otters were removed from the kelp forest.

32 Limpets in the genus *Lottia* are aquatic molluscs that feed on the green algae that grow on rocks on seashores. Black oystercatchers (*Haematopus bachmani*) are the birds that feed on limpets.

A study was conducted in the Monterey Bay area in California, USA to determine the density of two species of limpets (*Lottia digitalis* and *Lottia scabra*) on a vertical surface of sandstone. The results of the study are shown in the following graph.

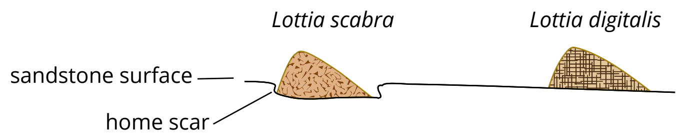


a Construct a food web to show the feeding relationship between the two species of limpets, the black oystercatchers and the green algae.

b Which species tend to dominate the upper areas of the vertical surface?

c Black oystercatchers are unable to climb vertical surfaces, so when they feed they tend to stay at the bottom of the vertical surface. The typical height of black oystercatchers is approximately 35 cm. Suggest which species of limpet is the preferred prey of black oystercatchers. Give an explanation for your answer.

d The following diagram shows a cross-sectional view of how each species of limpet adheres to sandstone. *Lottia scabra* secretes a substance that dissolves sandstone. By scraping the softened rock with its radula (a rough tongue-like structure), the limpet creates a 'home scar' in the rock surface.

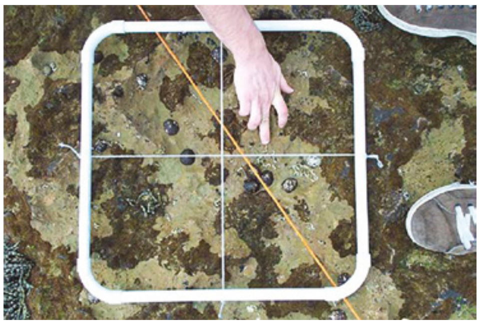


i State the type of adaptation displayed by *Lottia scabra*.

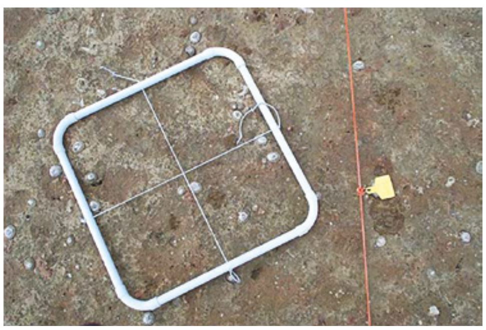
ii Suggest how the presence of a home scar would be an advantage for this limpet.

33 Students wanted to investigate the distribution patterns of periwinkles and brown algae at various distances from the high tide mark along an intertidal rocky shore. First, they made a transect line starting from the high tide mark (a). The students placed a quadrat (0.5 m × 0.5 m) at the 0 m mark on their transect. They counted the number of periwinkles in the quadrat and also determined the percentage of the quadrat covered by brown algae (b). The results of the survey are shown in the table to the right.

a



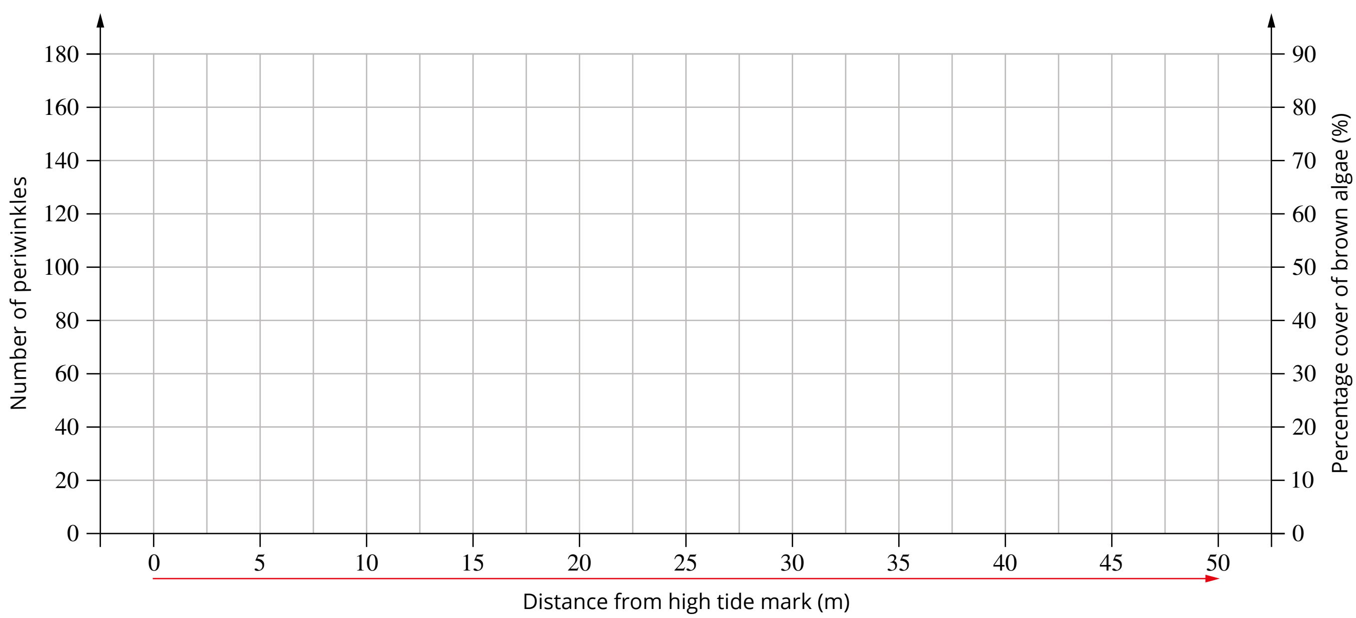
b



Distance from high tide mark (m)	Number of periwinkles in the quadrat	Percentage cover of brown algae in quadrat (%)
0	147	0
5	162	4
10	20	13
15	0	7
20	1	9
25	10	50
30	1	8
35	0	0
40	0	0
45	0	0
50	0	0

a Plot the results of the survey on the graph below.

Number of periwinkles and percentage cover of brown algae at different distances from high tide mark



b The students did some research on brown algae. They discovered that some brown algae contain phlorotannins, which act as a chemical defence against grazing organisms such as periwinkles. The students hypothesised that the change in the density of periwinkles along the transect from the high tide mark to the 50 m mark is due to the inability of periwinkles to graze on brown algae. Evaluate the students' hypothesis.

c Suggest how the reliability of the results could be improved.

34 Discuss how disturbance events are causing the Great Barrier Reef ecosystem to become less stable. Include climate change threats to the reef and their effects in your answer.

35 Below is an image showing copper contamination of a waterway in an abandoned mine site at Mt Oxide in North Queensland. Australia is home to more than 50 000 abandoned mines. Discuss what is involved in restoring these mining sites to productive, sustainable ecosystems.

Glossary

A

abiotic Relating to the non-living (physical and chemical) parts of the environment, such as water, soil and sunlight, as opposed to the biological (biotic) parts.

abscission The shedding of various parts of an organism, such as the shedding of leaves from a deciduous plant or the dropping of ripened fruit. From the Latin *ab*, away, and *scindere*, to cut (i.e. 'to cut away').

absolute dating (using radiometric methods) A direct quantitative method of determining the age of a rock or object using radioactivity.

abundance The number of individuals of a species that occur in a particular area.

accuracy The ability to obtain a correct value.

activation energy The energy that is required to start a biochemical reaction.

active site The specific site of the enzyme that binds the substrate and where catalysis occurs.

active transport The movement of substances across membranes that involves the use of energy.

adaptation (1) An inherited character that increases the likelihood of survival and reproduction of an organism or species. (2) The process by which a species becomes well-suited to its lifestyle and environment.

adaptive radiation A single species evolving into several species by adapting to the requirements of different environments and lifestyles. This process is often quite rapid.

adaptive value A measure of how well suited a particular phenotype is to a particular environmental condition and the likelihood of an individual with the allele that codes for the phenotype surviving and reproducing successfully. Alleles with high adaptive values tend to persist and increase in frequency in gene pools compared to those with low adaptive values.

adenosine diphosphate (ADP) A molecule produced by the release of energy from ATP. ADP may be converted back to ATP for re-use.

adenosine triphosphate (ATP) A molecule that provides energy for immediate use by a cell. It is produced during glycolysis and cellular respiration.

adhesion The tendency of dissimilar particles to stick to one another. For example, water molecules and the hydrophilic cell walls of the xylem of a plant.

ADP See *adenosine diphosphate*.

aerobic respiration The breakdown of glucose in the cell using oxygen, the energy from which is used to synthesise ATP. Aerobic respiration is comprised of glycolysis, the Krebs cycle and the electron transport chain.

aestivation A long period of torpor in hot and dry conditions. See also *hibernation*.

aim A statement describing in detail what will be investigated. See also *purpose*.

allele One of the alternative forms of a gene. Most genes have two alleles, but more than two alleles are possible.

allele frequency The relative proportion of a particular allele in a gene pool. Typically presented as a decimal or percentage of the allele of that gene in the gene pool.

allopatric speciation The divergent evolution of two new species from an ancestral species resulting from separation by a geographical barrier. The lack of gene flow between populations and the slight variations in environmental conditions of the two habitats drives natural selection in slightly different ways until the two populations become genetically distinct.

altitude The height above sea level.

alveoli Small air sacs in the lungs of mammals, located at the ends of the bronchioles. Alveoli have very thin cell walls surrounded by a network of capillaries, which enables efficient gas exchange across their surface.

amensalism A relationship between organisms of different species in which one of the organisms benefits and the other is harmed or killed. An example is a paralysis tick and its host. The tick benefits by feeding on the blood of its host, and the host suffers by becoming ill or possibly dying from the effect of neurotoxins injected by the tick.

amino acid An organic compound containing an amino group ($-NH_2$) and a carboxyl group ($-COOH$) at opposite ends of the molecule. Linked amino acids form the peptide chains in protein molecules.

ammonia A compound (formula NH_3) that is the first nitrogenous waste to be formed from the breakdown of proteins. Ammonia is highly toxic and is excreted mainly by aquatic animals.

amniotic The nutritious fluid surrounding an ovum.

amylase An enzyme that breaks down starch molecules.

anabolic Biochemical reactions that produce larger molecules from smaller substrates. Anabolic reactions are endergonic because they require energy to form bonds between molecules.

anaemia Condition in which there are fewer red blood cells or less haemoglobin than normal, reducing the amount of oxygen available to cells.

anaerobic respiration Not requiring or involving oxygen.

analogous feature Features (e.g. organ or structure) in different organisms that have the same function but have evolved independently and not from a common ancestor. Analogous features are the result of convergent evolution. Analogous features may evolve because unrelated organisms have experienced similar selection pressures.

ancestor An organism from which two or more species diverged.

angiosperm A vascular plant that produces flowers and seeds enclosed within an ovary (fruit, grain or nut). Angiosperms include most trees, shrubs, herbs and grasses.

anthropogenic pressure Selection pressure caused by human activity.

antibiotic A medicine used to control bacterial infection, via restriction of bacterial reproduction.

antifreeze protein (AFP) A group of polypeptides that inhibit the growth and recrystallisation of ice crystals by binding to them.

anus Opening at the lower end of the digestive tract through which solid waste passes.

aorta The large artery that carries blood from the left ventricle of the heart to the body.

arboreal Relating to trees; an animal that lives in or among trees.

Archaea A domain of living things consisting of bacteria that can live at high temperatures (thermophiles), in acidic environments (acidophiles) or very salty environments (halophiles). See also *Bacteria*, *prokaryote*.

artefact A human-made object that has cultural or historical significance.

arteriole A small blood vessel that stems from an artery and leads to capillaries.

artery A blood vessel with thick, elastic walls, through which blood flows from the heart to the rest of the body.

artificial selection The human-driven process where organisms with desirable traits are specifically selected for reproduction in order to pass on select traits to the next generation.

aspect The compass direction a slope of land faces.

asthma A condition in which the cells lining the bronchi and bronchioles become inflamed, narrowing the airways and making breathing difficult.

atmosphere The layer of gases surrounding the Earth, consisting of about 78% nitrogen, 21% oxygen, and 1% other gases and water vapour.

ATP See *adenosine triphosphate*.

atrium (pl. atria) A chamber of the heart that receives blood returning from the body or the lungs, before passing the blood into a ventricle. The left atrium receives oxygenated blood from the lungs, and the right ventricle receives deoxygenated blood from the rest of the body.

autoradiography A method for viewing radioactively-labelled tissues, cells, organelles or genetic material. The radioactively-labelled structures emit beta-particles that produce an image of the structures on photographic film.

autotroph An organism that is able to produce its own food from inorganic materials, using light or chemical energy. Plants that photosynthesise are the most common autotrophs. All autotrophs are producers.

auxin A plant hormone that is released from the growing tip and stimulates growth. Synthetic auxins are used as herbicides.

B

background extinction The average rate of extinctions for a certain group over time.

Bacteria A domain of living things consisting of bacteria that live on or in animals, plants, soil or water, in environments of moderate conditions. See also *Archaea*, *prokaryote*.

bacterium (pl. bacteria) All prokaryotes not members of the domain Archaea.

bar graph A graph in which categorical data are represented by horizontal bars. Each bar represents one category of independent variable (such as a range of values, or a particular type of thing), and the length of the bar represents the value of the dependent value for that range or thing.

basal metabolic rate The rate at which energy is used by an animal at rest.

behavioural adaptation Actions that an organism takes to improve an organism's ability to cope with abiotic and biotic factors in their environment, increasing their chances of survival and reproduction.

bilayer Double layer. For example, the lipid bilayer of cell membranes is two molecules thick.

bile A secretion produced by the liver and stored in the gall bladder, from where it is released into the small intestine. Bile acts as an emulsifying agent, physically breaking up large fat droplets into smaller droplets to increase the surface area of food being digested.

biochemical Relating to chemical processes within living organisms.

biodiversity The variety of all life forms—the different plants, animals and microorganisms, the genes they contain and the ecosystems in which they exist.

biodiversity hotspot a region that hosts a large amount of biodiversity and also experiences a lot of habitat destruction.

biogeochemical cycle The cycling of chemical elements through biotic and abiotic systems on Earth. For example, the water cycle, the nitrogen cycle and the carbon cycle.

biogeographic region An area inhabited by a unique set of animals and plants, indicating a common history or environment, for example the Australasian region or neotropical region.

biogeography The study of the distribution of organisms.

bioindicator Species that are used to measure conditions within an ecosystem.

biological control The use of a natural predator, parasite or other agent to limit and control the growth of a pest species. An example is use of the myxoma virus and calicivirus to control the European rabbit in Australia.

bioluminescence The production and emission of light by an organism, such as sea jellies, fireflies and luminous fungi. It is a form of chemiluminescence, in which light energy is produced following a chemical reaction.

biomass The mass of living matter per unit area (e.g. kg/m^2), or the equivalent amount of chemical energy bound in the mass of tissue (e.g. kJ/m^2). Biomass measurements may be for total biomass, or for the biomass of a particular group of organisms such as plants.

biome A group of communities that have similar structures and habitats extending over a large area.

biomimicry The design of products or materials modelled on the structures or systems found in nature. For example, the bullet train inspired by the beak shape of kingfisher birds.

bioprospecting The exploration of biodiversity for new resources that may have social or commercial value, such as new medicines.

bioresource A resource that is derived from a renewable biological process, such as fertiliser or medicinal plant products.

biosecurity Measures to detect, respond rapidly to and recover from pests and diseases, including introduced species, to protect agricultural production and wildlife biodiversity.

biosphere The region of Earth's land, sea and atmosphere that is occupied by living things.

biotic Relating to the biological parts of the environment, as opposed to the abiotic (physical and chemical) parts.

blastocyst The blastula stage in the development of a mammalian embryo. The blastocyst consists of an outer layer of cells that will develop into the placenta, an inner mass of cells that will develop into the embryo, and a fluid-filled cavity.

blastula An early stage of embryonic development in animals, coming after the morula stage. The blastula consists of a sphere of cells surrounding a fluid-filled cavity. It is during this stage that cell differentiation begins. In mammals the blastula is referred to as a blastocyst.

blood Specialised fluid, often containing cells, which is circulated to provide internal transport in animals.

blood plasma Fluid component of the blood that transports red blood cells, white blood cells, platelets, nutrients, hormones and proteins.

blood vessel Tubular structure that carries blood throughout the body.

Bohr effect Physiological phenomenon first described by Christian Bohr which states that the affinity of haemoglobin for oxygen is inversely related to the acidity of blood and the concentration (or partial pressure) of carbon dioxide.

bottleneck effect The resulting impact when a large portion of a population is removed from the habitat by chance, typically as a result of a natural disaster. The effect of genetic drift is more significant on the smaller population, as the remaining gene pool has reduced diversity.

bronchiole Small passages that branch off from the bronchi in the lungs.

bronchus (pl. bronchi) Two main passages that branch off from the trachea to the lungs.

brumation A type of torpor undergone by many reptiles. It is similar to hibernation but differs in the metabolic processes involved. Brumation begins just before winter and lasts between one and eight months.

C

caecum An intestinal pouch at the junction of the small and large intestine. In some herbivores, such as koalas, it is very enlarged and acts as a fermentation chamber for the digestion of cellulose.

calibrate To check the accuracy of a measuring device or instrument.

CAM (crassulacean acid metabolism) photosynthesis A form of photosynthesis that occurs in many plants growing in hot, dry environments. Stomata open at night to take in carbon dioxide, which is incorporated into malate. During the day the stomata are closed to reduce transpiration, and malate is metabolised to release carbon dioxide, which is then used by cells.

Cambrian explosion The apparently sudden appearance of fossils during the Cambrian.

capillary A tiny blood vessel with a wall only one cell thick, across which exchange occurs between blood and tissues.

carbohydrate An organic compound consisting only of carbon, hydrogen and oxygen atoms, with the hydrogen and oxygen atoms in the same proportion as in water (2 to 1). Carbohydrates include sugars and starches.

carbon dating Method for determining the age of an object using the rate of radioactive carbon decay. Objects between 5730 and 50 000 years old can be accurately dated using carbon dating techniques.

carbon dioxide Colourless, odourless gas that is used during photosynthesis and formed during cellular respiration.

carbon fixation The incorporation of carbon into organic compounds by living organisms.

cardiovascular system Organ system that transports blood, gases and nutrients throughout complex animals. Also known as the circulatory system.

carnivore An organism that feeds only on other animals.

carotid rete system A network of blood vessels that cools the brain by countercurrent heat exchange. It is present in humans and many other vertebrates.

carrier protein A transport protein that changes shape when molecules bind to it, so that the molecules can pass through the cell membrane. Carrier proteins take part in facilitated diffusion and active transport.

carrying capacity The maximum population of a species that can be supported indefinitely by an ecosystem.

Casparian strip A water-resistant strip in the endodermis of roots that regulates the entry of water and solutes.

catabolic reaction Biochemical reaction in which there is a breakdown of macromolecules into smaller molecules. Catabolic reactions are exergonic because they release energy.

catalyse To increase the rate of a reaction.

catalyst A substance that increases the rate of a reaction, without being consumed in the reaction (e.g. enzymes).

catalytic power The ability or potential of an enzyme to increase the rate of a biochemical reaction compared to the reaction occurring without the enzyme present.

cell The smallest structural and functional unit in a living thing. All cells have a cell membrane and contain cytoplasm, organelles and genetic material (DNA). In plants, fungi and monerans, cells also have a cell wall.

cell compartmentalisation The formation in the cytosol of specialised structures enclosed by membranes, including the nucleus, mitochondria, endoplasmic reticulum, Golgi apparatus, endosomes, lysosomes and chloroplasts.

cell differentiation The process by which a cell changes from one type to another. This is usually an unspecialised cell becoming a specialised cell.

cell membrane A bilayer (double layer) of phospholipids that encloses the contents of a cell and controls the movement of substances into and out of the cell. Also called plasma membrane.

cell replication The process by which a single cell divides into two or more daughter cells.

cell specialisation The specialised function performed by a cell. Examples of specialised cells are red blood cells, nerve cells and muscle cells in animals, and root hair cells and guard cells in plants.

cell wall An external structure that surrounds the cell membrane for structural support and protection. Composed of cellulose (in plants) or peptidoglycan (in bacteria).

cellular respiration The energy-releasing processes that occur in cells. In particular, the aerobic stage in the complete breakdown of glucose to produce ATP, which occurs in mitochondria and produces 36 or 38 molecules of ATP per molecule of glucose.

cellulase Enzyme that catalyses the reaction that breaks down cellulose into glucose. Cellulase plays an important role in digestion in herbivores.

cellulose A complex carbohydrate molecule consisting of a chain of many glucose molecules. It is the main component of plant cell walls. Its formula is $(C_6H_{10}O_5)n$.

centriole A small cylindrical organelle consisting of a group of microtubules, and occurring as a pair in the centrosome in the cells of animals and some other organisms. Centrioles are replicated in the S phase, and the two pairs formed separate during mitosis and move towards the opposite ends (poles) of the cell.

channel protein A transport protein that molecules do not usually bind to. Channel proteins allow specific molecules to pass through the cell membrane, and are used in facilitated diffusion. See also *carrier protein*.

chemical digestion The action of enzymes in breaking down complex compounds into simple compounds that can be used for metabolism.

chemoautotroph Organism that produces energy using inorganic compounds (e.g. hydrogen sulfide).

chemoheterotroph A consumer organism (heterotroph) that gains its energy by carrying out energy-releasing reactions between inorganic molecules.

chemosynthesis (adj. chemosynthetic) The process by which organisms synthesise organic compounds from inorganic materials using the energy released by simple chemical reactions. Chemosynthesis occurs in some prokaryotes.

chemotropism Growth or movement in response to a chemical substance, either towards or away from the substance.

chlorenchyma Cells that make up the soft tissue in plants (parenchyma) and contain chloroplasts.

chlorophyll A light-absorbing pigment involved in photosynthesis.

chloroplast A green organelle in plant cells in which photosynthesis takes place. A chloroplast consists of many folded layers of membrane and contains chlorophyll.

cholesterol A steroid lipid found in most body tissues. Cholesterol is an important component of cell membranes in animals and is used to form other steroid compounds.

chromatid One of two copies of a chromosome formed during the S stage of interphase. The two copies, called sister chromatids, are joined at a centromere.

chromosome A complex structure consisting of DNA strands coiled around histone proteins, carrying the hereditary information of the cell in the form of genes. All body cells in a particular species have the same number of chromosomes.

cilium (pl. cilia) A hair-like structure on the surface of some eukaryotic cells, consisting of a '9 + 2' arrangement of microtubules enclosed by an extension of the cell membrane. Cilia move with an oar-like motion and are usually shorter and more numerous than flagella.

***cis* face** The side of the Golgi apparatus facing the nucleus.

cisternae Flattened sac-like membranes found in the Golgi apparatus and endoplasmic reticulum.

climate Weather conditions prevailing in an area over a long period.

climate zone Regions of distinct climates occurring in an east-to-west direction across Earth.

closed circulatory system A circulatory system in which the fluid (blood) is confined to vessels and is kept separate from the interstitial fluid.

codon The basic unit of the genetic code. A sequence of three nucleotides that codes for a particular amino acid, or indicates the beginning or end of translation.

coenzyme A small organic molecule that combines with an enzyme and is necessary for its activity.

coevolution The evolution of two species in response to one another such as those between pollinator and flowering plant or between parasite and host.

cofactor A chemical component such as a metal ion or coenzyme that is required for the proper function of proteins.

cohesion (adj. cohesive) Describes the attraction between particles of the same type, such as water molecules.

colony (adj. colonial) A group of organisms of the same species that live together.

column graph A graph in which categorical data are represented by vertical columns. Each column represents one category of independent variable (such as a range of values, or a particular type of thing), and the length of the column represents the value of the dependent value for that range or thing.

commensalism A relationship between two organisms in which only one benefits, but the other organism is not harmed.

common ancestor An organism from which two or more species diverged. Also known as shared ancestor.

community A group of species that occur in the same area and interact, or could interact, with each other.

companion cell In vascular plants, the small cells that occur next to sieve-tube cells in phloem, and arise from the same parent cell.

comparative anatomy The study of the similarities and differences between the anatomical structures of animals.

comparative embryology The study of evolutionary relationships and homologies visible in embryos.

competition An interaction between organisms that are seeking to use the same resource, such as food, water, shelter, sunlight or mates.

competitive exclusion The displacement of one species by another species due to competition for the same resources. See also *competitive exclusion principle* and *outcompete*.

competitive exclusion principle The principle that states that two species competing for the same limited resource cannot co-exist or have the same niche in an ecosystem.

competitive inhibition The inhibition of an enzyme due to a molecule that binds to the active site of the enzyme, preventing the substrate from binding.

concentration gradient A difference in the concentration of a solute between one region and another; for example, across a membrane.

confocal microscope instrument used to view sections of a cell or tissue that have been stained with fluorescent markers, without actually sectioning or slicing the cells. Confocal microscopy can obtain high-resolution (high-quality) images of very thin sections of a specimen.

connective tissue Tissue that connects, separates or supports tissues or organs in the body.

conservation The preservation and protection of biodiversity.

conservation triage Frame-work for prioritising the species or regions that are most in need of conservation.

conservative substitution A change in the nucleotide sequence of DNA or RNA that leads to the replacement of one amino acid with a functionally similar one, and having little or no impact on the protein synthesised.

consumer An organism in a food chain that feeds on other organisms.

continental drift The gradual movement of continents on Earth's surface.

continuous variable A variable that can have any number value within a given range.

control group A group of subjects in an experiment that is identical to the experimental group and is treated in an identical way, except that the variable of interest (the independent variable) is kept constant.

controlled variable The variables that are kept constant during the investigation.

convergent evolution The evolution of similar features in unrelated groups of organisms (i.e. they do not share a recent common ancestor). For example, wings in birds and bats look similar and have the same function but evolved independently.

coprophagy Reingestion of faeces to absorb essential nutrients. This practice is common in animals with hindgut fermentation such as rabbits and possums.

coronary circulation The movement of blood through the heart muscles. Blood is supplied via arteries from the base of the aorta, and returns to the lungs via veins from the right atrium.

countercurrent heat exchange The process of cooler blood from the nostrils passing in the opposite direction to the warmer blood from the body, allowing the heat to flow from the hotter blood to the cooler blood in the neighbouring network of blood vessels. Countercurrent heat exchange is a physiological adaptation of animals living in hot environments.

crista (pl. cristae) The folded structures of the inner membrane of a mitochondrion.

crowding High density of individuals in an area which results in negative effects for individuals and populations as resources become increasingly limited.

cyanobacteria Formerly called blue-green algae; a photosynthesising bacteria.

cytology The study of cells.

cytoplasm The fluid cytosol of a cell, together with the organelles that it surrounds.

cytosol The fluid part of cytoplasm, surrounding all of a cell's organelles except the nucleus.

D

Darwinism The theory of biological evolution by natural selection developed by Charles Darwin. Also known as Darwin's theory.

data The measurements or observations collected during an investigation.

database Organised collection of information or data.

deciduous Adjective describing a tree or shrub that sheds its leaves annually. May also be used to describe milk teeth or 'baby teeth' in mammals.

decomposer An organism that breaks down dead or decaying organisms or organic wastes. Decomposers are mainly bacteria and fungi.

dehydrin A protein produced in plants in response to cold or drought. Dehydrins bind to proteins and water molecules inside the cell and stabilise the cell membrane and enzymes.

denature (or denaturation) An irreversible change in the tertiary structure of a protein, as a result, for example, of heating the protein above a critical temperature.

density-dependent factor A limiting factor whose effect depends on the size of the population.

density-independent factor A limiting factor whose effect does not depend on the size of the population.

dentition Relating to teeth.

deoxygenated blood Blood that has no oxygen. Blood carries oxygen to the cells, where it is needed for cellular respiration, and exchanges it for carbon dioxide at the cell membrane. Deoxygenated blood then circulates back to the lungs to receive more oxygen.

deoxyribonucleic acid (DNA) A nucleic acid made up of a sequence of nucleotides, each with a deoxyribose sugar, phosphate and base (adenine, cytosine, guanine or thymine), linked by phosphodiester bonds. DNA is the carrier of genetic information in all living things and most viruses. It occurs in chromosomes in the nucleus or nucleolus, and also in mitochondria and plastids.

dependent variable The variable that is measured to study the effect of changes in the independent variable.

dephosphorylation A reaction that involves the removal of a covalently coupled phosphate group from another molecule.

descriptive statistic Statistics that summarise data. Measures of frequency, measures of central tendency, measures of variation and measures of position are descriptive statistics.

detritivore An organism that obtains its nutrients from decomposing organisms or wastes expelled by animals.

detritus Organic matter consisting of the remains of dead organisms or wastes expelled by animals.

developmental biology The study of development in embryos.

diaphragm Sheet of muscle that sits below the lungs and plays an important role in inhalation and exhalation.

diastolic pressure Blood pressure caused by the contraction of the ventricles of the heart. The lower diastolic pressure occurs when the ventricle relaxes.

diffusion The passive movement of a solute from a region of higher concentration to a region of lower concentration.

digestion The breakdown of food into a form that can be used by an organism for metabolism. Digestion involves mechanical digestion and chemical digestion.

digestive enzyme An enzyme that assists in the digestion of otherwise indigestible matter.

diploid Having two sets of chromosomes (2n). All somatic cells are diploid.

disaccharide A sugar formed when two monosaccharides are joined together, with the loss of a water molecule. Sucrose and lactose are common examples of disaccharides.

discrete variable A variable that can have only certain values. For example, the number of individuals in a population can only be whole numbers.

disease Disorder in the structure and function of an organism.

disturbance Change in environmental conditions that can cause a significant change in an ecosystem. For example, natural disasters or habitat clearance.

divergent evolution The evolution of two or more different species from a common ancestral species.

diversity Variation in life forms, such as genetic diversity, species diversity and ecosystem diversity. See also *biodiversity*.

DNA See *deoxyribonucleic acid*.

DNA sequence The sequence of bases in a fragment of DNA. DNA sequences can be used to determine relationships between individuals of a species, and for determining the entire genome of an organism.

DNA sequencing The determination of the sequence of bases in a fragment of DNA. DNA sequencing can be used to determine relationships between individuals of a species, and for determining the entire genome of an organism.

domain The largest grouping in the classification of living things. See *Bacteria*, *Archaea*, *Eukarya*.

dormancy The state in which an organism's growth, development and activity temporarily slows, or stops, in order to conserve energy in response to environmental conditions.

E

ecological niche The role of an organism or group of organisms in an ecosystem, including its position in the food web, how it obtains its food and how it reproduces.

ecosystem A system formed by organisms interacting with one another and their physical environment.

ecosystem restoration Process of restoring damaged ecosystems.

ecosystem service Processes carried out in ecosystems that contribute to the quality of life for humans. For example, oxygen production by plants, food production, climate control, crop pollination and cultural and recreational benefits.

ectoderm The outermost layer of the three primary germ layers in the early embryo.

egestion Elimination of food that has not been absorbed by the gut.

electron microscope A microscope in which a beam of electrons is used to form an image of an object.

embryo The stage in the development of a vertebrate, between the fertilisation of the ovum and the development of the characteristics of the adult.

emigration The movement of individuals out of a population.

emphysema Condition in which the air sacs in the lungs break down, reducing the surface area available for gas exchange.

endemic Occurring only in a particular area. For example, the Tasmanian devil is endemic to Tasmania.

endergonic Biochemical reaction in which energy is absorbed.

endocytosis The movement of material into a cell by enclosing it in cell membrane, which then pinches off to form a vesicle within the cell. Endocytosis includes phagocytosis (the entry of solids) and pinocytosis (the entry of liquids).

endoderm The innermost layer of the three primary germ layers in the early embryo.

endosome Membrane-bound vesicles in cells. The endosome contains molecules brought into the cell by the process of endocytosis.

endosymbiotic theory The theory that states that prokaryotes and archaea merged to form eukaryotes.

endotherm (adj. endothermic) An animal that maintains a more or less constant body temperature, which is usually higher than the temperature of the surrounding environment.

environmental resistance The sum of the factors (abiotic and biotic) that limit population growth in an environment.

enzyme A protein molecule that catalyses (speeds up) biochemical reactions.

enzyme–substrate complex The complex that forms when an enzyme binds to a substrate.

eon One of several subdivisions of geologic time enabling cross-referencing of rocks and geologic events from place to place. Eons are the largest subdivisions.

epidermis The outermost layer of cells of a multicellular organism.

epiglottis A thin flap of cartilage that covers the entrance to the larynx, preventing food from entering the trachea while eating.

epithelium (adj. epithelial) A thin layer of tissue covering the external surfaces of a multicellular organism, and also lining the inner surfaces of internal structures such as intestines and lungs.

epoch One of several subdivisions of geologic time enabling cross-referencing of rocks and geologic events from place to place. Epochs are the smallest subdivisions.

equilibrium A state of stability in which opposing factors are balanced.

era One of several subdivisions of geologic time enabling cross-referencing of rocks and geologic events from place to place. Eons are larger subdivisions than eras; eras may be divided into periods and epochs.

error The difference between the true value and the measured value.

essential amino acid An amino acid that cannot be produced from other amino acids and therefore must be obtained in the diet. Essential amino acids for humans are histidine, isoleucine, leucine, methionine, phenylalanine, threonine, tryptophan, valine and lysine.

ethics Moral principles that govern behaviour and decision-making.

Eukarya The domain that includes all eukaryotes.

eukaryote An organism whose cells contain a membrane-bound nucleus and other membrane-bound organelles. Protists, fungi, plants and animals are eukaryotes.

eutrophication Excess nutrients in a body of water that can cause over-growth of algae. Eutrophication is often caused by run-off of fertiliser from agriculture entering water ways.

evaporative cooling The release of heat from the body via evaporation. Sweating and panting are forms of evaporative cooling.

evolution The cumulative change in the inheritable characteristics of organisms, expressed as the development of new forms or species.

ex situ Meaning 'out of place' or 'out of position'. Ex situ conservation refers to conservation of species outside their natural habitat.

excretion The removal of waste substances from the body of an organism.

exergonic Biochemical reaction in which energy is released.

exocytosis A type of active transport in cells in which molecules such as proteins are expelled from a cell. The molecules are enclosed by a vesicle, which then fuses with the cell membrane and expels the contents into the extracellular fluid.

experimental group The group of subjects in an experiment in which one variable (the independent variable) is altered in order to measure its effect on another variable (the dependent variable). See also *control group*.

exponential growth The growth of a population in which rate of growth is proportional to population size. A graph of exponential growth shows an increasing gradient over time.

exponential relationship A mathematical relationship in which the rate of change of one variable is proportional to the value of the other variable.

external environment The environment immediately surrounding a cell or an organism.

extinction The dying out of a species; when individuals of a species no longer exist.

extracellular digestion Chemical digestion in which the enzymes are secreted into a cavity, where digestion takes place.

extracellular fluid The fluid outside the cells in a multicellular organism.

extremophile An organism that lives in an extreme environment, such as somewhere with a very high pressure, temperature or salinity.

F

facilitated diffusion Diffusion of ions and molecules through a cell membrane via ion channels and channel proteins. Facilitated diffusion does not require chemical energy from the conversion of ATP to ADP.

facultative colony A colony of largely independent organisms that gather together in response to environmental conditions in order to increase their chances of survival.

facultative mutualism Mutualism in which the individuals do not depend on each other for survival, but both benefit from the relationship.

facultative symbiosis Type of symbiosis in which each species benefits from the interaction but are not dependent on one another for survival.

falsifiable A hypothesis, theory or statement that can be proven false.

feedback inhibition The inhibition of enzyme activity by a product that is produced later in the biochemical pathway. Feedback inhibition is an important mechanism in controlling enzyme activity.

feeding interdependency A feeding relationship between species in an ecosystem.

fermentation The stage in the breakdown of glucose that follows glycolysis when there is no oxygen present. Fermentation produces either lactic acid (in most animals) or alcohol (in most plants and micro-organisms).

fertilisation Penetration of an egg by sperm and fusion of the egg and sperm nuclei.

filtration In the kidney, the process by which the primary kidney filtrate is formed, from fluid passing from Bowman's capsule into the nephron.

fimbriae Specialised hair-like projections on the surface of prokaryotic cells that allow the cells to attach to surfaces (e.g. the intestinal wall of animals).

fitness An organism's suitability to its environment.

flaccid Drooping or soft. In plant tissue, guard cells become flaccid when they lose water.

flagellum (pl. flagella) An organelle involved in movement (of the cell or things around the cell).

fluid mosaic model Describes the structure of the cell membrane in which phospholipids and unanchored proteins are free moving, giving the membrane fluidity. Anchored proteins are scattered throughout, giving the membrane a matrix pattern.

fluorescence microscope Instrument used to examine cells, cellular structures or any fluorescing material, such as stains, dyes or antibodies, with fluorescent molecules.

food chain A sequence of feeding relationships, beginning with a producer and ending with a higher order consumer. The producer is eaten by a first-order consumer, the first-order consumer is eaten by a second-order consumer, and so on.

food vacuole Membrane-bound sacs inside cells that contain digestive enzymes.

food web A network of interlinked food chains that describes the feeding relationships between all organisms in an ecosystem.

fossil The preserved remains, impressions or traces of organisms found in rocks, amber (fossilised tree sap), ice or soil.

fossil record The record of the evolution of organisms through geological time based on information from fossils.

fossilisation The process of preservation of the hardened remains, impressions or traces of organisms in rocks.

founder effect Occurs when a small portion of a population disperses to a new location and becomes genetically isolated from the main population. The allele frequencies of the founding population are completely dependent on those of the specific individuals that were relocated, and therefore may be significantly different from those of the original population.

fungi (singular fungus) Eukaryotic organisms consisting of heterotrophs, which are composed of hyphae and reproduce by spores. The kingdom Fungi includes mushrooms, lichens (lichenised fungi), yeasts and moulds.

G

gall bladder Organ that stores and concentrates bile before releasing it to the small intestine.

gamete A haploid cell capable of fusion with another haploid cell to form a zygote. In vertebrates the gametes are sperm and egg cells.

gene A section of DNA that contains instructions for making a protein. Particular genes have specific locations on chromosomes. Genes are copied and passed from one generation to the next during reproduction.

gene expression The process that leads to the transformation of the information stored in a gene into a functional gene product (usually a protein or RNA molecule).

gene flow The movement of alleles between individuals of different populations; includes the dispersal of pollen and seeds in plants.

gene pool All the alleles possessed by members of a population, which may potentially be passed to the next generation.

generalist Organism that is adapted to a broad range of conditions (i.e. not specialised).

genetic drift Random changes to allele frequencies in a gene pool as the result of a chance event. This has a more significant impact on smaller populations, as the chance death of one individual could eliminate an allele from the gene pool.

genetic variation Variation in genes or alleles within a population or species. Also called genetic diversity.

genome The DNA in one full set of chromosomes present in the nuclei of normal cells of a species, plus the DNA in mitochondria and (in plants) chloroplasts.

genophore A single, usually circular DNA chromosome in a prokaryote, containing the genetic material.

genotype (adj. genotypic) (1) The total set of genes of an organism. (2) The combination of alleles for a trait carried by an individual.

genus (pl. genera) In the classification of organisms, the category above the species level. Similar genera are grouped into families.

geographic distribution The geographic extent of a group of organisms. It is commonly applied to the extent of a population or species. Also called geographic range.

geological time scale System of chronological dating based on geological formations and events throughout Earth's history.

geotropism Plant growth in response to gravity.

germ layer The primary layer of cells that are formed during embryogenesis. Animals with bilateral symmetry have three layers: endoderm, mesoderm and ectoderm. Animals with radial symmetry have two layers: endoderm and ectoderm.

gill Respiratory organ in aquatic animals.

glucose A simple sugar (formula $C_6H_{12}O_6$) that is a product of photosynthesis. It is the main source of energy for cells in living things, and is essential for cellular respiration.

glycerol A trihydric alcohol (a compound with three hydroxyl groups) found in plant and animal cells. Lipids are broken down into fatty acids and glycerol, which are some of the final products of digestion.

glycogen A complex carbohydrate molecule consisting of glucose subunits. Glycogen is the main carbohydrate storage molecule in animals.

glycolipid A lipid with a carbohydrate group attached. It is a component of the cell membrane and is a marker for cell recognition.

glycolysis The first stage in the breakdown of glucose to produce ATP. Glycolysis occurs in the cytoplasm and produces two molecules of ATP for each glucose molecule.

glycoprotein A protein that has a carbohydrate group attached to the polypeptide chain. Glycoproteins are components of the cell membrane and are receptors for molecules such as hormones.

Golgi apparatus (also known as Golgi body, Golgi complex) An organelle composed of a stack of cisternae in which proteins are assembled and then packaged in vesicles for exocytosis.

Gondwana A supercontinent of the past that formed when the process of plate tectonics united the land masses of the Southern Hemisphere and included present-day Africa, Madagascar, India, Australia, Antarctica and South America.

gram-negative Bacteria with a thin layer of peptidoglycan in their cell wall. When stained with crystal violet dye, gram-negative bacteria do not retain the dye and are pink (negative Gram staining result).

gram-positive Bacteria with a thick layer of peptidoglycan in their cell wall. When stained with crystal violet dye, gram-positive bacteria retain the dye and are purple (positive Gram staining result).

granum (pl. grana) A stack of thylakoids in the chloroplast.

gravitropism Plant growth in response to gravity.

guard cell Specialised epidermal leaf cells bordering stomata. Stomata open when the guard cells are turgid (swollen).

guttation The loss of liquid water from leaves as a result of root pressure.

H

habitat The environment where an organism lives.

habitat fragmentation Division of habitat into smaller, less continuous sections due to processes such as forest clearance and urbanisation.

haemocoel Open, fluid-filled space in the open circulatory systems of arthropods.

haemoglobin A protein molecule in red blood cells that carries oxygen from the lungs, and returns carbon dioxide from the tissues to the lungs. Haemoglobin occurs in mammals and many other animals, and gives red blood cells their characteristic colour.

haemolymph Circulatory fluid in the open circulatory systems of arthropods.

half-life The time it takes for half of the parent atoms in a radioactive material to turn into daughter atoms. Used in radiometric dating techniques.

halophyte A plant adapted to growing in a salty environment.

heart Muscular pumping organ that moves internal fluids (usually blood) in complex animals.

heat exchanger A mechanism for exchanging heat between an organism and its environment.

herbivore An animal that feeds only on producers, such as plants or algae.

heredity The process of passing on characteristics (heritable traits) from parents to offspring, or from one generation to the next.

heterotroph An organism that must obtain nutrients from other organisms.

hibernation A long period of torpor during the colder months of the year. See also *aestivation*.

homeostasis (adj. homeostatic) The maintenance of a more or less stable internal environment, even when external conditions change.

hominin Member of the subfamily Homininae, which includes humans, chimpanzees, gorillas and extinct species of *Homo*, *Australopithecus*, *Paranthropus* and *Ardipithecus*.

homologous features Structures that have a common evolutionary origin, which is evident in the underlying fundamental similarities in their structure. Homologous features are found in different organisms and may have evolved different functions (e.g. a human hand and a bat wing) as a result of divergent evolution from a common ancestor. DNA sequences or proteins can also be homologous.

horizontal gene-transfer The ability of microbes to acquire new genes and traits from unrelated species.

hormone A molecule that regulates the growth or activity of those cells capable of responding to it (target cells). Hormones are produced by specialised groups of cells within an organism.

host An organism that carries a parasite.

hybrid An individual produced by a cross between parents with different genotypes.

hybrid inviability A hybrid that cannot survive beyond the zygote stage.

hydrolysis A chemical reaction involving the splitting of a molecule by the addition of a water molecule at a particular point.

hydrophobic Repelling water. Hydrophobic substances do not wet easily and do not dissolve in water. (Compare to *hydrophilic*.)

hydrophilic Having an affinity or attraction to water. Hydrophilic substances easily mix and dissolve in water. (Compare to *hydrophobic*.)

hydrosphere The watery regions of the Earth, consisting of the oceans, seas, lakes, streams and groundwater.

hydrostatic pressure Pressure exerted by a fluid. For example, the pressure exerted by sap in the sieve-tube cells of vascular plants.

hydrotropism Plant growth in response to a water concentration gradient.

hypertonic solution A solution that has a greater concentration of solutes compared to another solution or inside normal body cells.

hypothesis A tentative explanation that is based on observation and prior knowledge. A hypothesis must be testable and falsifiable (can be proven false).

hypotonic solution A solution that has a lower concentration of solutes compared to another solution or inside normal body cells.

I

ice core A long cylindrical sample of ice that is taken from glaciers or ice sheets. Ice cores contain evidence of past changes in the environment, such as levels of atmospheric carbon dioxide.

igneous rock Rock formed from the cooling and crystallisation of magma and lava.

immigration The movement of individuals into a population.

immune response Activation of the body's immune system due to the presence of a foreign body or organism.

impression fossil A type of fossil where the impression of the external or internal surface of the organism is preserved.

innate behaviour Behaviour that is inherited rather than learnt; an instinctive response.

in situ Meaning 'in place' or 'in position'. Studies that are in situ are undertaken on biological structures in their natural position, such as cells functioning in a tissue or organ. In situ conservation refers to the conservation of species within their natural habitat.

in vitro Meaning 'in glass'. In vitro processes are undertaken in a test tube or Petri dish such as cell or tissue cultures.

in vivo Meaning 'in the living'. Studies that are undertaken in living organisms.

inbreeding The loss of genetic variation within a species.

independent variable The variable that is altered during an experiment to test its effect on another variable (the dependent variable). Also called experimental variable.

index fossil A fossil that is used to define and identify geologic periods.

individual A single organism.

infection The severe, uncontrolled growth of a foreign organism inside another.

infer To deduce something from evidence or reasoning.

inference Something that is inferred.

inorganic compound Any compound that does not include carbon. However, oxides, carbonates, bicarbonates, carbides and cyanides are usually also considered to be inorganic compounds.

inquiry question A question that defines the focus of an investigation.

instant speciation When hybrids having the same chromosomal mismatch find each other and reproduce to form a new species.

integral protein A protein that is a permanent part of the cell membrane.

interbreed The ability of members of a species to reproduce with each other and produce fertile offspring.

intermediate disturbance hypothesis Hypothesis that proposes that high and low levels of disturbance reduce the species diversity of an ecosystem. Species diversity is maximised when disturbances are at an intermediate level.

internal environment The watery extracellular fluid that surrounds the cells of a multicellular organism.

interspecific Interactions between or involving two or more different species (e.g. interspecific competition).

intracellular digestion The breakdown of particles that takes place in the cytoplasm of a cell.

intracellular fluid The fluid inside a cell.

intraspecific Interactions between or involving two or more individuals of the same species (e.g. intraspecific competition).

invasive species Species outside its native range that has a negative impact on the environment, native species, the economy or human health.

inverse relationship A mathematical relationship in which one variable increases when the other decreases.

invertebrate Animal without a vertebral column (spine) such as octopus, insects, molluscs and crustaceans.

isotonic solution A solution that has an equal concentration of solutes compared to another solution or inside normal body cells.

isotope One of two or more atoms that have the same atomic number (the same number of protons) but a different number of neutrons; for example, carbon-12 and carbon-14.

K

keystone species A species on which the entire structure and functioning of an ecosystem depends. Without the keystone species, the ecosystem structure would change significantly, and the ecosystem would function in a very different way.

kidney Organ involved in filtering the blood and producing urine in complex animals.

L

lactation Milk production by mammals.

lacteal Vessels of the lymphatic system close to the small intestine. Lacteal capillaries absorb digested fats from the small intestine, giving the lacteals a milky appearance.

lactic acid Compound produced during anaerobic cellular respiration.

Lamarckism The theory of evolution proposed by Jean-Baptiste Lamarck that states that a particular trait is enhanced or diminished within the lifetime of an individual, depending on its use and that the modified trait is inherited by offspring.

lamellae Thin layer or membrane; membranous fold in a chloroplast.

large intestine Last portion of the digestive system in complex animals. The large intestine absorbs water and stores faeces before egestion.

larynx The organ in the upper trachea that contains vocal cords and is responsible for speech in humans. It is also involved in breathing and in preventing the aspiration of food or other large particles into the lungs.

Laurasia A supercontinent of the past formed by the land masses of the Northern Hemisphere near the end of the Palaeozoic era.

lenticel A porous group of cells that allows gas exchange across the otherwise airtight and waterproof cork layer covering the stems and roots of woody plants.

life cycle Biological cycle through which organisms undergo a series of changes.

light compensation point The light intensity at which the rate of oxygen produced by photosynthesis equals the rate of oxygen use in cellular respiration in a plant.

light microscope (LM) Microscope that uses light and a system of lenses to magnify the image.

light-dependent reaction The reactions in photosynthesis in which light captured by chlorophyll is used to split water to produce oxygen, and ATP and NADPH for use in the light-independent reactions.

light-independent reaction The reactions in photosynthesis in which the energy in ATP and NADPH from the light-dependent reactions is used to fix carbon into carbohydrates. These reactions are part of a biochemical pathway called the Calvin cycle.

lignin A complex organic compound deposited in the cell walls in the xylem vessels, tracheids and supporting tissue of vascular plants. Lignin gives strength to the stem and other plant parts. It is not present in non-vascular plants such as mosses.

limiting factor Any factor that prevents a population from growing larger. Common limiting factors are the availability of water, food, shelter, nesting sites and mates.

line graph A graph in which the relationship between the variables is represented by a straight line, curved line or series of line segments.

line of best fit A straight line drawn between data points on a graph that shows the overall trend in the data and can be used to predict values between data points. See also *trend line*.

linear relationship A mathematical relationship between variables in which a change in one variable produces a proportional change in the other variable. The graph of a linear relationship is a straight line.

lipase An enzyme that digests lipids.

lipid An organic compound that is insoluble in water but soluble in alcohol, ether or chloroform. Lipids include fats, oils, sterols, some hormones, fat-soluble vitamins, glycerides and phospholipids.

lithosphere The solid outer layers of the Earth, including the crust and the solid part of the mantle below it.

liver A large organ in vertebrates that is involved in many important metabolic processes, including protein manufacturing, fat storage and processing, bile secretion and metabolism of toxins.

local extinction The dying out of a population; when individuals of a population no longer exist in a particular region.

logistic growth Population growth in which the growth rate decreases as the population approaches the carrying capacity. A graph of logistic growth is an S-shaped curve.

lumen (1) The region enclosed by the cell membrane of a cell. (2) The inside of a tubular structure such as a blood vessel or xylem tube.

lymph The fluid that circulates in the lymph system. It consists mainly of interstitial fluid (fluid forced from capillaries by blood pressure into the spaces between tissues) and contains lymphocytes, macrophages, proteins and fats. It has an important role in defending the body against harmful bacteria and other particles, and also in the absorption and transport of fatty acids.

lymphatic system The body system that transports immune cells including antigen-presenting cells throughout the body, and is where antigen recognition by lymphocytes occurs; important for adaptive immune responses in mammals.

lymphocyte A type of leukocyte involved in adaptive immune responses; includes B and T lymphocytes.

lysosome An organelle vesicle containing digestive enzymes used in the digestion of waste and foreign material.

M

macroevolution Evolutionary change above the species level over long periods of evolutionary time. (Compare with *microevolution*.)

macroinvertebrate Invertebrate (animal without a vertebral column) that can be seen without the aid of a microscope.

maladaptive Not adapted to the environment. Selection pressures will remove maladaptive (disadvantageous) traits from the population.

malic acid Organic compound found in fruit. Plants that carry out crassulacean acid metabolism (CAM photosynthesis) store carbon dioxide as malic acid.

maltose A sugar formed by the digestion of starch. It is a disaccharide consisting of two glucose molecules.

mark–recapture Fieldwork technique in which animals are captured, tagged (marked) and released. Populations are then resampled at a later date and the population size estimated based on the number of animals recaptured.

marsupial A subclass of mammals characterised by a pouch for carrying the young, which are born immature and complete their development in the pouch.

mass extinction Large-scale worldwide extinctions evident in the fossil record and caused by major disruptive changes to global climate and the shifting of continents.

mean The average value of a set of values, calculated by dividing the sum of the values by the number of values.

measure of central tendency Single values that describe the central position in a set of data.

measurement bias A type of systematic error that is caused by instruments that are faulty or not calibrated, or the incorrect use of instruments.

median The value in the middle of an ordered list of values.

megafauna The giant animals known from fossil evidence to have once inhabited Australia; ancestors of many present-day Australian species.

meiosis A division of a nucleus that results in one copy of each homologous chromosome and one sex chromosome in each daughter cell. Meiosis produces four genetically unique daughter cells, each with half the number of chromosomes of the parent cell.

meniscus The curved upper surface of liquid in a tube or container, caused by surface tension. A meniscus can be concave (as in water in a glass tube) or convex (as in mercury in a thermometer).

meristem Tissue in plants that contains undifferentiated cells and is the site of cellular differentiation and specialisation. Meristem tissue usually occurs at the tips of roots and shoots of plants, where most tissue growth occurs.

mesoderm The middle layer of the three primary germ layers in the early embryo. The mesoderm is present only in animals with bilateral symmetry; animals with radial symmetry have only two primary germ layers.

mesophyll Thin-walled, loosely packed photosynthetic plant tissue that forms most of the interior of leaves.

metabolic Relating to the biochemical processes carried out to sustain life. See also *metabolism*.

metabolic rate The rate at which energy is required by an organism to maintain homeostasis.

metabolism The total of the physical and chemical processes by which energy and matter are made available by an organism for its own use. Metabolism is controlled by enzymes.

metamorphic rock Rock formed after exposure to extreme pressure or heat.

methanogen A prokaryote that uses carbon dioxide to produce methane (CH_4).

microevolution Evolutionary change in alleles, populations and species over a short period of evolutionary time. (Compare with *macroevolution*.)

microhabitat Smaller areas within a habitat (e.g. burrow or tree canopy).

microvillus (pl. microvilli) A microscopic fold of the inner surface of intestinal epithelial cells. Microvilli increase the surface area for the absorption and secretion of substances.

midden A historic site of human occupation where people left debris from their meals.

mid-ocean ridge Underwater mountain range formed where two tectonic plates meet causing the ocean floor to lift.

migration The geographic movement of organisms.

mimicry Resemblance of a structure or behaviour between animal or plant species. Mimicry may be a form of camouflage or a defence mechanism against predators.

mineral Any naturally occurring inorganic substance. In nutrition, important minerals include elements such as magnesium, potassium, calcium, iron and sodium. Minerals in foods are essential for maintaining biological functions.

mineralised fossil Fossil in which minerals replace the spaces in the structure of the organism such as bone. Minerals may eventually replace the entire organism, leaving a replica of the original fossil.

mitochondrial DNA (mtDNA) DNA found in the mitochondria.

mitochondrion (pl. mitochondria) Organelles in which cellular respiration occurs. Each mitochondrion is composed of many layers of folded membrane.

mitosis A division of a nucleus that results in two cells that are genetically identical to the parent cell. Asexual reproduction and cell replication for growth occur by mitosis.

mode The value that occurs most often in a data set.

model Representations of structures or processes, such as physical models or digital models, that are used to create and test theories and explain concepts.

model organism Organisms that are commonly used in scientific experiments such as mice, the fruit fly *Drosophila melanogaster*, the plant *Arabidopsis thaliana* and the bacterium *Escherichia coli*.

molecular clock The estimated rate of mutation in a region of DNA. It is used to estimate the rate of evolutionary change.

molecule (adj. molecular) Smallest unit in a chemical element. Molecules come together to form compounds (e.g. H_2O).

monitoring Process of researching and gathering information about a variable to assess the state of a system or population and record changes over time.

monosaccharide Any of various simple sugars that are the basic unit of carbohydrates. They include glucose, fructose and galactose.

monotreme The group of egg-laying mammals including the platypus and echidna.

morphology The physical form or structure of an organism.

mortality The death rate in a population, usually expressed as number of deaths per unit of population in a given time period. For example, the death rate in Australia in 2013 was 6.4 per 1000 population.

mouth First part of the digestive system of animals where food is mechanically digested by chewing and saliva is produced for chemical digestion.

mRNA (messenger RNA) An RNA molecule that is transcribed from DNA in the nucleus, then passes into the cytoplasm and binds to a ribosome, where it is used to build an amino acid sequence (polypeptide).

multicellular Consisting of two or more specialised cells that have identical DNA, are responsible for specific functions, and depend on each other for survival. Also called pluricellular.

mummified organism A type of fossil in which the organism is fully preserved and may include features such as skin, fur and organs.

mutation A permanent change in the base sequence of DNA. Mutations may occur spontaneously or in response to radiation or harmful substances.

mutation rate The rate at which genetic mutations occur over time.

mutualism A symbiotic relationship between two organisms in which both organisms benefit. An example is pollination of flowers by insects, in which the insect receives nutrition and the plant is able to reproduce.

myoglobin A red respiratory pigment that occurs in muscles. Myoglobin carries oxygen that can be used when other oxygen reserves are depleted.

N

nastic movement A movement of plant tissues in response to an environmental stimulus, such as a change in humidity or temperature. Nastic movements are independent of the direction of the stimulus.

natality The birth rate in a population, usually expressed as number of births per unit of population in a given time period. For example, the birth rate in Australia in 2014 was 12.8 per 1000 population.

natural disaster Natural event such as an earthquake, flood or bushfire.

natural selection The mechanism by which evolution is believed to occur. Some individuals in a population have inherited characteristics that make them more likely to survive and reproduce than others in the population. These individuals then pass these characteristics on to their offspring. Over time this removes less suitable variations, so that evolutionary change gradually occurs.

negative feedback loop A control system in which the response produced by a stimulus reduces the size of the original disturbance. This eventually leads to homeostasis.

nephron The functional unit of the kidney; consisting of a Bowman's capsule surrounding a glomerulus and a tubular region leading into a collecting duct. About 1 million nephrons are found in each human kidney.

nitrogen Chemical element with the symbol N.

nitrogenous waste Waste products from the breakdown of proteins, including ammonia, urea and uric acid.

nominal variable A categorical variable in which there is no inherent order. Nominal variables can be counted but not ordered.

non-competitive inhibition The inhibition of an enzyme due to an inhibiting molecule binding to an allosteric site on the enzyme. This causes a conformational change in the active site of the enzyme that prevents substrate from binding, or otherwise prevents a catalytic reaction from proceeding even if substrate is bound.

non-conservative substitution A change in the nucleotide sequence of DNA or RNA that leads to the replacement of one amino acid with a functionally different one, resulting in biochemical changes.

nondisjunction The failure of homologous pairs of chromosomes to separate during metaphase I of meiosis. Non-disjunction results in aneuploidy because two of the gametes formed will have two copies of the chromosome, while the other two gametes will be missing that chromosome entirely.

nucleic acid A long-chain molecule formed from nucleotides. The nucleic acids DNA and RNA are the genetic material of all organisms. They determine the physical appearance of an organism and how it functions.

nucleoid The structure in prokaryotes that contains genetic material.

nucleolus (pl. nucleoli) A dark-staining body in the nucleus, where ribosomal RNA is synthesised.

nucleotide A molecule consisting of a 5-carbon sugar (ribose in RNA, or deoxyribose in DNA), a nitrogenous base (purine or pyrimidine) and a phosphate group. Nucleotides are the building blocks of nucleic acids such as DNA and RNA.

nucleus An organelle that contains genetic information (used for the synthesis of proteins) and directs the activities of the cell.

nutrient A substance that provides nourishment for growth and reproduction.

O

objective Free of personal bias.

objective lens The lens in a microscope that is closest to the object being viewed.

obligate colony A colony of individuals that carry out specific functions and must live together in order to survive.

obligate mutualism Mutualism in which one of the organisms cannot survive without the other.

obligate symbiosis Relationship between species that is necessary for survival.

observation A value or other information obtained during an experiment.

ocular lens The lens in a microscope that is closest to the user's eye. Also known as the eyepiece.

oesophagus Muscular tube that transports food from the mouth to the stomach in complex animals.

omnivore An organism that feeds on both plants and animals.

open circulatory system A system for fluid circulation in animals in which there is no clear distinction between circulatory and interstitial fluids, so that fluids flow more or less freely between the cells of the tissues.

optimum range The organism is best suited to the environmental conditions and is able to outcompete.

ordinal variable A categorical variable in which there is an inherent order. Ordinal variables can be counted as well as ordered.

organ A structure, consisting of different tissues, that carries out one or more specific functions.

organelle Any specialised structure in the cytoplasm of a cell, including the Golgi apparatus, mitochondrion, endoplasmic reticulum, vacuole, chloroplast and nucleus.

organic compound Any chemical substance containing carbon, once thought to come from living organisms. Common organic compounds are proteins, carbohydrates and lipids. However, oxides, carbonates, bicarbonates, carbides and cyanides are usually not considered to be organic compounds.

organic solute Organic chemical compound dissolved in solution (e.g. sucrose dissolved in water).

organism A living system that functions as an individual, whether unicellular or multicellular.

osmoconformer Marine organism that maintains a concentration of solutes (dissolved substances) in their body that is equal (isotonic) to their surroundings.

osmolarity The concentration of a solution, measured in osmoles of solute per litre of solution. Also called osmotic concentration.

osmosis Passive diffusion of free water molecules across a semipermeable membrane from a more dilute solution to a more concentrated solution.

osmotic gradient A difference in the concentration of a solute (dissolved substance) on each side of a semipermeable membrane.

osmotic pressure The pressure that causes free water molecules to move along a concentration gradient (osmotic gradient) across a semipermeable membrane. It is caused by a difference in concentration of the solutions on each side of the membrane.

outcompete To displace another species in the competition for space, food or other resources. See also *competitive exclusion*.

outlier A data point that lies outside the main group of data.

overexploitation Harvesting natural resources at a rate that is faster than natural populations can replenish.

ovum The female reproductive cell in animals which, once fertilised by a sperm, will develop into an embryo. Also known as a gamete.

oxygen Chemical element with the symbol O. Oxygen is an essential element in the biological processes of photosynthesis and cellular respiration.

oxygenated blood Blood that has oxygen. Blood carries oxygen to the cells, where it is needed for cellular respiration, and exchanges it for carbon dioxide at the cell membrane.

oxygen-carrying capacity The amount of oxygen that can be carried by a particular medium, such as blood.

P

palaeontology The study of ancient life preserved as fossils in rocks and ancient sediments.

palisade mesophyll The regularly arranged rectangular cells beneath the epidermis of a leaf.

pancreas Organ of the digestive system of complex animals that produces digestive enzymes.

Pangaea The supercontinent of enormous land mass that formed when Laurasia (northern land mass) and Gondwana (southern land mass) united by the end of the Palaeozoic (225 million years ago).

parallel evolution The independent evolution of similar traits in response to similar selection pressures.

parapatric speciation Speciation that occurs in populations that are not geographically isolated, but where there is significant variation in habitat conditions within the range of the original population.

parasite (adj. parasitism) An organism that lives in or on another organism and benefits by feeding on nutrients.

parasite–host food chain Feeding interdependency between a parasite and its host.

parenchyma Cells that make up the soft tissue of a plant. Parenchyma cells have various roles in photosynthesis (chlorenchyma cells), storage and wound repair.

passive transport Movement of liquid or gas through cell membranes without using any energy, e.g. diffusion and osmosis.

peer-review Evaluation of professional work or research by scientists to check that the work meets scientific standards and is appropriate for publication.

peptidoglycan A giant molecule that forms a mesh-like layer on the outside of the cell membrane of most bacteria. Each molecule consists of glycans (large-molecule sugars) linked by chains of amino acids. Also called murein.

period One of several subdivisions of geological time enabling cross-referencing of rocks and geologic events from place to place. Eons and eras are larger subdivisions than periods, while periods themselves may be divided into epochs.

peripatric speciation Speciation that occurs in small populations that have become spatially isolated from the main population.

peripheral protein A protein that is a temporary part of the cell membrane. Peripheral proteins bind to integral proteins or penetrate the periphery (outside layer) of the cell membrane.

peristalsis Coordinated muscular contractions and relaxations of the wall of the digestive tract that move a bolus of food from the oesophagus to the intestines.

permeable membrane A membrane that allows substances to pass through it.

personal protective equipment (PPE) Clothing and equipment worn to improve safety. For example, a laboratory coat, safety glasses and latex gloves should be worn when working in a laboratory, while sunscreen, a hat and sturdy shoes should be worn when doing fieldwork.

petrification A process of fossilisation in which minerals replace the spaces in the structures of organisms such as bones. Also called mineralisation.

pH A measure of the acidity or alkalinity of an aqueous solution. It is measured on a logarithmic scale from 0 (most acid) to 14 (most alkaline). A solution that is neither acid nor alkaline has a pH of 7, and is said to be neutral.

phagocyte Cell capable of engulfing pathogens or foreign particles to destroy them.

phagocytosis The process by which a solid particle in the extracellular fluid is taken into a cell. The particle is enclosed by a section of cell membrane, which then pinches off to form a vesicle within the cell's cytoplasm. Phagocytosis is a type of endocytosis.

phagosome A vacuole in a cell's cytoplasm that contains a phagocytosed particle.

pharynx Cavity behind the nose and mouth through which food passes from the mouth to the oesophagus and air passes from the nose to the trachea.

phenotype (adj. phenotypic) (1) An observable character or trait of an organism. (2) The overall appearance of an organism.

phloem Plant tissue through which sugars and other organic compounds are distributed to different parts of a plant. In flowering plants, phloem consists of sieve tubes, companion cells and fibres.

phospholipid A fat-like substance, usually based on glycerol. Phospholipids are essential components of cell membranes. They are involved in the uptake of fats and fatty acids from the products of digestion.

phosphorylation The process of adding a phosphate group to a molecule. Phosphorylation is a common way of activating enzymes and other functional molecules.

photoautotroph Organism that uses light energy to produce organic compounds during photosynthesis.

photoheterotroph A consumer (heterotroph) that obtains its energy from light.

photolysis A chemical reaction in which molecules are separated by light energy. This occurs during the light-dependent reaction of photosynthesis, where water molecules are separated into hydrogen and oxygen atoms.

photometer An instrument that measures the intensity of light.

photonasty Plant movement in response to a change in light intensity.

photosynthesis (adj. photosynthetic) The process by which plants and other photosynthetic organisms convert energy from sunlight into chemical energy for biological functions. It occurs in plastids.

phototropism Plant growth in response to light.

phylogeny The evolutionary relationship between organisms, commonly represented by a diagram called a phylogenetic tree.

physical digestion The process of mechanically breaking down food into small pieces to improve the efficiency of chemical digestion.

physiological adaptation Functional and biochemical reactions that take place in organelles, cells, tissues, organs, systems, or the whole organism to improve an organism's ability to cope with abiotic and biotic factors in their environment, increasing their chances of survival and reproduction.

pie chart A circular diagram divided into sectors, with each sector representing the value of one set of data as a proportion of the total data set.

pinocytosis The process by which a mass of fluid is taken into a cell. The fluid is first surrounded by a section of cell membrane, which then pinches off to form a vesicle within the cell. Pinocytosis is a type of endocytosis.

placental The group of mammals excluding marsupials and monotremes.

plagiarism Claiming that another person's work is your own.

plasma membrane See *cell membrane*.

plasmid A fragment of DNA that is outside the chromosomes, in the cytoplasm. Plasmids usually include genes and can replicate independently. In genetic engineering, bacterial plasmids can be used to produce recombinant DNA.

plasmodesma (pl. plasmodesmata) A microscopic channel that connects the cytoplasm of adjacent cells in plants and some algae.

plastid A large organelle with a double membrane found in plant cells. Plastids contain their own DNA.

plate tectonics The theory that Earth's crust is divided into separate plates, which move on a layer of semi-liquid rock in the mantle. Collisions of plates can form mountain ranges or deep-sea trenches, and the separation of plates can widen oceans and form new sea floors.

platelet Component of the blood that plays a role in clotting. Also called thrombocyte.

pluricellular Composed of different cell types.

pneumonia Infection of the lungs that causes the alveoli to become inflamed and fill with white blood cells and fluid, reducing the surface area available for gas exchange.

point mutation A type of gene mutation that typically only affects a single nucleotide. Types of point mutations include substitution and frameshift mutations.

point sampling Sampling of organisms at particular geographic points.

polar zone Regions at the poles of Earth (North and South Poles).

pollution The introduction of toxic or harmful substances to the environment.

polymerase chain reaction (PCR) A technique used to make millions of identical copies of a segment of DNA in a short period of time.

polypeptide A long, chain-like molecule consisting of many amino acids linked together. Each amino acid loses a water molecule when it is linked, so a polypeptide is actually a chain of amino acid residues. The group of atoms (–NH–CO–) that links each amino acid to the next one is called a peptide bond.

polyploid Having more than one copy of the full complement of chromosomes. Common polyploid states are diploid (two copies), triploid (three copies) and tetraploid (four copies).

polysaccharide A long chain of linked monosaccharides. Polysaccharides include starch, glycogen and cellulose. Also called glycan.

population A group of organisms of the same species that interact with each other.

population density The number of individuals in an area.

population explosion A very rapid increase in the size of a population of organisms.

positive feedback loop A control system in which the response produced by a stimulus increases the size of the original disturbance.

postzygotic isolating mechanism A process that stops successful gene flow between different species by causing reproductive failures after fertilisation. Common forms of postzygotic isolating mechanisms are hybrid inviability, reduced hybrid viability, hybrid sterility and hybrid breakdown.

precision The ability to consistently obtain the same measurement.

predation The killing and consumption of an animal by another animal.

predator An animal that kills and consumes other animals.

predator–prey food chain Feeding interdependency between a predator and its prey.

prey An animal that is a food source for another animal.

prezygotic isolating mechanism A process that stops successful gene flow between different species by preventing fertilisation. Common forms of prezygotic isolating mechanisms include spatial, temporal, ecological, structural and behavioural isolation.

primary data Data from an investigation that you have conducted yourself. Also called first-hand data.

primary investigation An investigation that you conduct yourself.

primary productivity Rate at which energy is produced by the plants (producers) in an ecosystem.

primary source A source that includes first-hand information, such as the results of an original experiment. See also *secondary source*.

principle A scientific theory that is so strongly supported by evidence that it is considered unlikely to be shown to be untrue in the future.

procedure Method or process for conducting an activity, experiment or investigation.

processed data Data that has been mathematically manipulated.

producer An organism that obtains its nutrition from non-living sources by photosynthesis or chemosynthesis. Plants, algae, phytoplankton and some bacteria are producers.

prokaryote An organism with cells that do not have a membrane surrounding the nucleus and lack most organelles. All prokaryotes are bacteria. See also *Archaea*, *Bacteria*.

protease An enzyme that digests proteins.

proteasome Protein complexes in eukaryotes.

protected area Area of habitat set aside for conservation of biodiversity.

protein A nitrogenous organic compound consisting of one or more long chains of amino acids.

protist Eukaryotic organism that is usually unicellular. Protists are a diverse group that belong to the kingdom Protista and include protozoa, slime moulds, water moulds and many algae.

Protista See *protist*.

protocol A detailed description of how an experiment or investigation will be conducted.

pseudopodia A temporary protrusion of the cytoplasm of a cell (such as an amoeba or a white blood cell) that functions especially as an organ of locomotion or in taking up food or other particulate matter.

pulmonary artery Artery that carries blood from the right ventricle of the heart to the lungs for oxygenation.

pulmonary circulation Part of the cardiovascular system that carries deoxygenated blood from the heart to the lungs and returns oxygenated blood back to the heart.

pulmonary vein In humans, a blood vessel that carries oxygen-rich blood from the lungs to the left atrium of the heart.

punctuated equilibrium Rapid periods of evolution followed by long periods of stability.

purpose A statement describing in detail what will be investigated. See also *aim*.

pyruvate A molecule produced from the splitting of glucose during cellular respiration.

Q

quadrat An area (usually a square) within which a biological survey (such as counting plants or identifying species) is carried out.

qualitative data Data that consists of categorical variables.

qualitative variable A variable that can be observed but not measured. Qualitative variables can be sorted into groups such as colour or shape. Nominal and ordinal variables are qualitative variables.

quantifiable Able to be measured or counted.

quantitative data Data that consists of numerical variables.

quantitative variable A variable that can be measured such as temperature or height. Discrete and continuous variables are quantitative variables.

R

radioactive decay The regular measurable rate of decay of an isotope.

radioactive isotope Isotopes are alternative forms of the same chemical element, e.g. carbon-12 and carbon-14. Radioactive isotopes have unstable nuclei, which spontaneously emit radiation.

radiometric dating Technique used to calculate the age of rocks and minerals using radioactive isotopes.

random error Unpredictable variations that can occur with each measurement.

random selection A selection that is not affected by bias.

range The difference between the highest and lowest values.

raw data The data recorded during an experiment.

reabsorption In the kidney, the process by which the primary kidney filtrate is taken back into the tissues via nephrons.

reaction A chemical process in which substances react to form new substances.

receptor-mediated endocytosis A method of transport of specific substances into a cell. A receptor in the cell membrane binds to a molecule, triggering its entry into the cell via a vesicle formed from the cell membrane.

receptor A specialised structure that can detect a specific stimulus and initiate a response.

rectum The final portion of the large intestine.

red blood cell Cell containing haemoglobin which binds to oxygen and transports it around the body. Also called erythrocyte.

relative dating Method of dating geological deposits based on the relative order of layers (strata) and, if present, the fossils within those layers. It is assumed that the deepest layer is the oldest and the uppermost layer is the youngest.

reliability The ability to reproduce your results.

remnant Small patch of habitat or vegetation.

repeat trial An experiment that is conducted again, in exactly the same manner as a previous experiment.

replication (1) Experimentation carried out on more than one set of subjects at the same time. (2) The production of new cells by cell division.

Representative Concentration Pathways (RCPs) Greenhouse gas concentration trajectories used for climate modelling research. RCPs provide different greenhouse gas concentration scenarios based on assumptions about technology, population growth, and the way humans generate energy and use land.

reproduction Production of new individuals via sexual or asexual reproduction.

reproductive isolation Separation of individuals via geographic or biological boundaries, preventing interbreeding.

reserve Protected area of habitat for biodiversity conservation.

resilient An ecosystem that can return to its normal structure and function after a disturbance.

resistant (1) An organism in which a target control method no longer works. For example, antibiotic resistance. (2) An ecosystem that is tolerant to disturbances and remains fundamentally the same over a long period of time with little deviation from its average state.

resource (1) Anything required by an organism for its survival and reproduction. (2) A source of information.

resource partitioning Different species use different parts of a resource at the same time.

ribonucleic acid (RNA) Nucleic acids involved in ribosome structure and protein synthesis. There are three forms: messenger RNA (mRNA), ribosomal RNA (rRNA) and transfer RNA (tRNA).

ribosome A small organelle composed of protein and RNA. Ribosomes are often attached to rough endoplasmic reticulum and are the site of protein synthesis.

risk assessment A systematic way of identifying the potential risks associated with an activity.

RNA See *ribonucleic acid*.

rock painting Art work on rock formations.

root hair A very thin extension of an epidermal cell of a root. Root hairs increase the root's surface area, making the absorption of water and minerals from soil more efficient.

root pressure Osmotic uptake of water that accompanies the active uptake of mineral salts and contributes to the movement of water up xylem in some plants.

rough endoplasmic reticulum Layers of intracellular membranes associated with ribosomes. Rough endoplasmic reticulum is involved in protein synthesis.

rRNA (ribosomal RNA) The RNA part of a ribosome. It is synthesised in the nucleolus and is essential for protein synthesis.

rumen A large fermentation chamber for the digestion of cellulose, located before the stomach in many herbivorous animals, such as cattle and sheep.

ruminant An animal with a rumen.

S

Safety Data Sheet (SDS) A document that provides health and safety information about hazardous chemicals or products.

salinity The concentration of salts (mainly sodium chloride) in water or soil.

salivary gland Gland in and around the mouth of animals that produces saliva containing digestive enzymes.

sample size The number of observations, measurements or replicates in an experiment or investigation.

saprotroph An organism that feeds on dead or decaying organic matter.

scanning electron microscope (SEM) Microscope that produces images by scanning the surface of an object with a beam of electrons.

scatterplot A graph in which two variables are plotted as points. The x coordinate of a particular point is one measured value of the independent variable and the y coordinate is the corresponding measured value of the dependent variable.

scientific method The systematic, objective collection of data by experiment in order to determine whether predictions based on a particular hypothesis are correct.

sclerenchyma Cell that provides strength and structural support for a plant. Sclerenchyma cells are fibres, such as stems and roots, and sclereids, such as the outer layer of seeds or nuts.

sclerophyll plant Vegetation type that is adapted to dry conditions and is common in Australia. Plants characteristically have short, hard leaves and include *Eucalyptus*, *Banksia* and *Acacia*.

secondary data Data you have not collected yourself.

secondary source A source of information that does not include first-hand information (primary data). See also *primary source*.

secondary-sourced investigation An investigation that uses data obtained by someone else (secondary data).

section In microscopy, a very thin slice of a specimen prepared by embedding the specimen in paraffin wax, and using a slicing instrument called a microtome to cut sections of just one layer of cells.

sedimentary rock Rock formed from the cementation of layered sediments (small rock fragments).

selection bias A type of systematic error that is caused by non-random sampling, resulting in a sample that is not representative of the population.

selection pressure Any environmental factor which affects the behaviour, reproduction and/or survival of an organism.

semi-conservative substitution A change in the nucleotide sequence of DNA or RNA that leads to the replacement of one amino acid with one that is similar in structure but has different biochemical properties.

semipermeable membrane A membrane that allows only some molecules to pass across it by osmosis or diffusion. Also called partially permeable membrane, or selectively permeable membrane.

sexual reproduction Reproduction involving the fusion of two gametes (egg and sperm), which are the haploid products of meiosis.

sexual selection The difference in the ability of individuals to acquire mates. It typically involves contests between males or choice by females and leads to the selection of characteristics relating to mate attraction. Individuals that possess the desired characteristic are more likely to mate and pass on their desired alleles to the next generation. The desired trait, such as number of eye spot feathers in peacocks, is often an indication of overall health and fitness and other alleles of high adaptive value.

shelter Structure that provides plants and animals with protection from abiotic factors, such as rain, or biotic factors, such as predators. Shelter also provides space for growth, development and social activity.

sieve-tube cell Elongated living cell found in phloem tissue, through which fluids and dissolved sugars are transported throughout the plant.

significant figure The number of digits that contribute meaning to a measurement. All non-zero digits and zeros between non-zero digits are significant figures. Zeros that follow non-zero digits after a decimal place are also significant figures. For example, 5.10 has three significant figures and 5.1 has two significant figures.

simple diffusion Movement of molecules across a membrane without the use of channel proteins or carrier proteins.

sink A site where something is stored or consumed.

small intestine Part of the digestive system between the stomach and large intestine in complex animals. The small intestine is the site of nutrient absorption.

smear In microscopy, a sample of cells that have been suspended in fluid and smeared on a slide.

smooth endoplasmic reticulum (SER) A continuous membrane system that forms a series of flattened sacs within the cytoplasm of eukaryotic cells. It is not associated with ribosomes and is involved in the synthesis of lipids.

solute A substance dissolved in a fluid (the solvent).

solvent A fluid in which a substance (the solute) is dissolved.

source (1) A site where something is produced. (2) A document or person from which information has been obtained.

specialist Organism that is adapted to a narrow range of conditions.

speciation The formation of a new species following a lineage-splitting event. Speciation may result from geographic, anatomical, physiological or behavioural barriers to breeding, leading to gradual divergence over evolutionary time, or may be rapid as a result of adaptive radiation.

species (1) A group of organisms that interbreed in the wild (or could do so) and produce viable, fertile offspring, but cannot produce viable, fertile offspring if they interbreed with organisms outside the group. (2) A category or group in the binomial system.

species distribution model Model that predicts a species' geographic distribution based on environmental data from locations where it is known to occur.

species richness The abundance of species per unit area.

specificity Relating to enzymes that bind to only one substrate and catalyse only one type of reaction.

specimen A sample that has been collected and preserved for investigation, such as cells, tissue or a whole organism.

sperm The male gamete in animals, which can move by the motion of a flagellum. Also called spermatozoon.

spiracle (1) In insects, the external opening of the trachea, through which gases are exchanged with the environment. (2) In fish, the small anterior (first) gill-slit, which is usually closed in most bony fishes.

spongy mesophyll The irregularly arranged cells with large air spaces between them in a leaf.

spontaneous mutation Any naturally occurring random change in DNA.

starch A complex carbohydrate consisting of glucose subunits. It is the main form of energy storage in plants.

stem cell A cell that can differentiate into a specialised cell.

stimulus An environmental factor that an organism can detect and respond to.

stoma (pl. stomata) Pores in the leaf epidermis, bounded by specialised guard cells that open and close the pore. Stomata are the main routes through which gas exchange occurs in plants, and through which water loss is regulated.

stomach Muscular organ of the digestive system of complex animals.

stratigraphy The study of the relative positions of layers of rock (strata), some of which contain fossils. The lowest stratum is the oldest and upper strata are progressively younger.

stratum (pl. strata) Rock-layers.

stroma (pl. stromata) The fluid matrix part of a chloroplast in which the light-independent reactions occur.

stromatolite A layered rock that forms when certain marine prokaryotes bind thin films of sediment together; includes fossil and present-day rocks.

structural adaptation Anatomical or morphological features that improve an organism's ability to cope with abiotic and biotic factors in their environment, increasing their chances of survival and reproduction.

subjective Influenced by personal views.

suboptimum range The organism can survive within the environmental limits, but may be outcompeted by better-adapted species.

substrate A molecule that is acted on by an enzyme.

surface-area-to-volume ratio The relationship between the surface area and volume of a structure. As the size of a structure increases, its surface-area-to-volume ratio decreases.

symbiont An organism that has a close, long-term association with another organism. See also *symbiosis*.

symbiosis A close association between two different organisms, in which at least one of the organisms benefits from the association. Symbiosis includes mutualism, commensalism and parasitism.

sympatric speciation The evolution of new species from a common ancestor, while occupying the same geographic range.

system A group of organs in animals that work together for a particular purpose. The major systems in humans are the integumentary system, skeletal system, circulatory system, muscular system, digestive system, nervous system, endocrine system, respiratory system and excretory system.

systematic error A consistent error that occurs every time you take a measurement.

systemic circulation Part of the cardiovascular system that carries oxygenated blood from the heart to the body and returns deoxygenated blood back to the heart.

systolic pressure Blood pressure caused by the contraction of the ventricles of the heart. The higher systolic pressure occurs when the ventricle contracts.

T

taxonomy The classification and naming of organisms according to their similarities and differences. Modern taxonomy uses both the appearance of organisms (morphology) and their DNA structure (genetics) to classify organisms.

tectonic plate Pieces of Earth's crust that glide over the mantle.

temperate zone Zone that lies between the tropics and the polar regions of Earth.

temporal partitioning Species that avoid competition by using the same resources at different times (e.g. diurnal and nocturnal species).

terrestrial Relating to land or Earth.

testable Something that is able to be experimentally tested. Hypotheses must be testable.

tetrapod A vertebrate (which includes amphibians, reptiles and mammals) with four limbs. Animals that had four-limbed ancestors (e.g. snakes and whales) are also known as tetrapods.

theory A hypothesis that is supported by a great deal of evidence from a wide variety of sources.

therapod The group of bipedal dinosaurs to which birds belong.

thermonasty Plant movement in response to temperature change.

thermoreceptor A sensory receptor that detects and responds to temperature.

thermoregulation Process used by some animals to maintain their internal (core) temperature.

thigmonasty Plant movement in response to touch.

thigmotropism Plant growth in response to touch.

threshold The point past which irreversible change cannot occur.

thylakoid A membrane-bound compartment inside a chloroplast. Thylakoids are the site of light-dependent reactions in photosynthesis.

thylakoid lamella (pl. thylakoid lamellae) The sheet-like thylakoid membranes between the grana in a chloroplast.

tidal volume The volume of air moved into and out of lungs during breathing.

tissue A group of similar cells functioning together.

tissue culture A method of growing cells or tissues in an artificial medium containing essential nutrients, salts and growth factors.

tolerance range The range of environmental conditions (such as temperature or salinity) that an organism can tolerate without injury.

tonoplast The membrane surrounding the vacuole in a plant cell.

topography The shape and features of the surface of a land mass, including artificial and natural features.

torpor A state of inactivity or dormancy in animals, in which the body temperature is lower and the metabolism is slower than normal.

trace fossil (or ichnofossil) Preserved evidence of an animal's activity or behaviour, such as footprints, without containing parts of the organism.

trachea Airway from the pharynx to the bronchi in complex animals.

tracheae Fine internal air-filled tubes in the open circulatory system of arthropods.

tracheid A long, hollow cell with a thickened wall and tapering ends, found in the xylem of vascular plants. Tracheids transport water and nutrients to the living cells of the plant.

trait A particular characteristic or feature of an organism.

***trans* face** The side of the Golgi apparatus facing the cell membrane.

transect A line along which a biological survey is conducted. Transects are used mainly in botanical surveys.

transitional series A series of fossils that shows evolutionary changes from one form to another.

translocation The transport of organic substances in the phloem of a vascular plant.

transmembrane protein An integral protein that spans both phospholipid layers of the cell membrane.

transmission electron microscope (TEM) Microscope that produces images by passing electrons through a very thin section of an object. A whole image is produced at once, instead of scanning across the object as in scanning electron microscopy (SEM).

transpiration The loss of water from the leaves of plants through stomata. Transpiration causes suction, which draws water up xylem vessels from the roots.

transpiration stream The flow of water within a plant, from the uptake by the roots to the loss of water to the environment via the leaves.

transpiration-cohesion-tension theory Theory that explains the movement of water through a plant, against the force of gravity, using the cohesion between water molecules and the tension (differential pressure) that draws water through the xylem.

Trend A pattern of change over time. Scientific data and models are used to understand trends, from which predictions about future changes can be made.

trend line A straight line drawn between data points on a graph that shows the overall trend in the data and can be used to predict values between data points. See also *line of best fit*.

trophic level The position of an organism in a food chain. For example, an organism that feeds on producers is a first-order consumer, and an organism that feeds on that first-order consumer is a second-order consumer.

tropical zone Zone that lies closest to the equator of Earth.

tropism Plant growth in response to an external stimulus such as gravity, light or water. The plant might grow towards the stimulus (positive tropism) or away from it (negative tropism).

tunica Meaning 'layer', such as the layer in an artery wall.

turgor (adj. turgid) The rigid state or fullness of a plant cell caused by internal fluid pressure (turgor pressure) acting on the cell wall. Turgor is maintained by the osmotic intake of water into the cell.

U

uncertainty The range of values within which the true value of a measured quantity probably occurs. Uncertainty is caused by random and systematic errors.

unicellular An organism consisting of a single cell.

urea A water-soluble molecule (CH_4N_2O) that is a major product of protein breakdown. It is excreted by many vertebrates, including mammals.

uric acid A complex nitrogenous compound ($C_5H_4N_4O_3$) that is produced and excreted by birds and most land reptiles.

urine Liquid by-product of metabolism in complex animals.

V

vacuole An organelle involved in storage in plant cells.

validity The extent to which an experiment or investigation accurately tests the stated hypothesis and purpose.

valve A specialised structure in circulatory systems that allows movement in one direction only. In humans, valves occur in the heart, veins and lymph vessels.

variable A factor or condition that can change during an experiment.

vascular (adj. vascularised) Having vessels that transport fluids.

vascular bundle A grouping of vascular tissues in vascular plants, containing both xylem and phloem. Vascular bundles are continuous, from the roots into the stem, branches and leaves.

vascular plant A plant that has vascular tissues (xylem and phloem) in which the cell walls contain lignin. All living plants, except bryophytes, are vascular plants.

vascular tissue The tissue that conducts water and nutrients from the roots to the leaves in vascular plants. It consists of two types of tissue: xylem and phloem. Vascular tissue also provides structural support to a plant.

vasoconstriction The narrowing of the internal diameter of a blood vessel.

vasodilation The widening of the internal diameter of a blood vessel.

vein A blood vessel that carries blood towards the heart. All veins except the pulmonary veins carry deoxygenated blood.

ventilation Active movement of air or water past gas exchange surfaces in animals. In land animals it is called breathing.

ventricle A muscular chamber of the heart that pumps blood from the heart to the rest of the body. In a four-chambered heart (as in humans) the right ventricle pumps deoxygenated blood to the lungs, and the left ventricle pumps oxygenated blood to other body tissues.

venule A small vessel that connects capillaries to a vein.

vertebrate An animal belonging to the phylum Vertebrata. Vertebrates have a brain enclosed in a skull, and a segmented spinal column consisting of vertebrae. They include fish, amphibians, reptiles, birds and mammals.

vesicle A small organelle consisting of a membrane filled with fluid. Vesicles are often involved in transport within the cell, but may have other functions.

vestigial structure A remnant structure of an organism that has lost all or most of its original function in the course of evolution.

viable offspring Members of the next generation who survive to maturity and are able to reproduce successfully.

villus (pl. villi) A tiny fold in the lining of the intestine. Villi increase the surface area available for the absorption of food.

vital capacity The maximum volume of air that can be moved into and out of the lungs in one breath.

vitamin Any organic compound required in small amounts for cell processes. In humans there are 13 such compounds, called vitamins A, B group (eight vitamins), C, D, E and K.

viviparous Having offspring that develop inside the mother and are released as live young. Viviparity occurs in most mammals, and in plants in which the seeds germinate while still attached to the parent plant (e.g. in some mangroves).

W

waste By-product of metabolism in organisms, such as carbon dioxide or nitrogenous waste (e.g. urea).

water Chemical element with the symbol H_2O. Water is an essential element in many biological processes.

white blood cell Cell in the blood involved in immune system processes. Also called leucocyte.

whole mount In microscopy, a whole organism or structure that is placed directly on a microscope slide.

xerophyte A plant adapted to dry conditions.

X

xylem The tissue in vascular plants that transports water and nutrients upwards from the roots. It consists of hollow chains of dead cells.

xylem vessel A long tube consisting of cells joined end to end, through which water and nutrients are transported from the roots to the leaves in a vascular plant.

Z

zooid A distinct, single organism which functions as part of a colonial organism. Also known as a polyp.

zygote A stage of animal development after fertilisation and before cell differentiation.

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